



**AN AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS:  
AN AGROCLIMATIC APPROACH FOR THE TRANSFER OF DRY-LAND AGRICULTURAL TECHNOLOGY**

**By  
SAZZALA JEEVANANDA REDDY**

**A thesis submitted for the degree of  
Doctor of Philosophy  
at the Australian National University.**

**June 1985**

**DECLARATION**

Except where otherwise acknowledged in the text,  
this thesis represents the original research of the author

*Sazzale Tevananda Reddy*

S. J. REDDY

This thesis is dedicated  
to my wife **Suguna**.

*S. J. Reddy*

S. J. REDDY

#### ACKNOWLEDGEMENTS

I am grateful to the Australian National University (Canberra) for financial support, the CSIRO (Canberra) for the use of research facilities, and my two supervisors Dr. N.S. McDonald (ANU) and Mr. H.A. Nix (CSIRO) for their valuable help. I am also thankful to Prof. Diana Howlett and Dr. G. McIntyre for their advice and comments on the final draft of the thesis.

I would like to express my sincere thanks to Mr. K.A. Cowan (for cartographic assistance) and Ms. Genessee Beadman (for typing) from the Geography Department (ANU); and Miss June McMahon, Dr. M. Hutchinson, Mr. Lee Belbin and Dr. T. Booth from the CSIRO for help in the analysis of data.

I also would like to express my gratitude to the Indian Meteorological Department (Poona), ORSTOM (Paris) and R.L. McCown (CSIRO, Townsville) for providing me with the daily rainfall data used in this thesis for India, west Africa and tropical Australia.



## ABSTRACT

In developing countries the major share of food production comes from rainfed or dry-land agriculture. Traditional crop production systems in these countries are remarkably homeostatic in that yields remain stable, but low. There are several ways of improving the dry-land agriculture: one such procedure is the transfer of well tested location-specific dry-land agricultural technology in which climatic analogues of an experimental site are identified by soil or climatic classifications.

The objective of the present study is to identify areas that are climatically suitable for dry-land or rainfed agriculture and to classify these regions into agronomically relevant homogeneous zones. This involves several steps: i) identification of the availability and accuracy of climatic data, and collection of such information; ii) identification or development of a suitable methodology to derive the agroclimatic variables that relate to farming systems and in particular to crop production systems; iii) identification of suitable classification procedures; and iv) interpretation of final results as relevant to the farming systems.

In this study the semi-arid tropics are considered to be synonymous with rainfed or dry-land agriculture in the tropics. The present study is restricted to the tropics, because a major part of the dry-land agricultural belt lies within the tropics and, also, the climatic limitations for crop production differ significantly from regions outside the tropics. A modified Thornthwaite method can be used to demarcate the semi-arid tropics, and this procedure has been adopted for India, Thailand, Africa, Brazil and Australia. Also, briefly the general features of the semi-arid tropical environment has been discussed.

A method, based on weekly rainfall and potential evapotranspiration of individual years, for deriving variables to classify the semi-arid tropics into relevant agronomically homogeneous zones has been presented. The method permits estimation of the available effective rainy period, the time of commencement of sowing rains, wet and dry spells within the effective rainy period and their variability over time, and an estimate of the likely

percentage crop failure years or, indirectly, the level of risk due to drought. These parameters allow a relevant and realistic assessment of the agroclimatic environment and agricultural production potential.

Regression analysis has been used to identify climatic differences between locations at different scales, i.e., local differences caused by orography, regional differences associated with circulation patterns and continental differences associated with general circulation patterns. For this study, data from 199 locations in India, Senegal and Upper Volta were used to produce three dissimilarity parameters. At a continental scale, despite a similar amount of mean annual rainfall, the growing season longer in west Africa than in India. Thus, in west Africa the corresponding wet and dry spells within the available effective rainy period are quite different from India. This difference will have its most obvious effect on farming systems in general, and crop management in particular. Eight agroclimatic variables related to crop production potential in the semi-arid tropics of India were identified. Using data from 80 locations in India, these variables were used to assess dry-seeding feasibility, water-logging hazards, risk in agricultural production, cropping patterns and their spatial distribution.

Identified agroclimatic variables which are relevant to crop production potential have been analysed and discussed. A soil-water balance simulation, and agronomic data for selected locations in India, have been used to assist in this analysis. Based on these observations the successful cropping systems and crop species for similar soil types are also discussed. Clearly, the cropping pattern is not only influenced by the duration of the mean available effective rainy period but also by its variability, as well as the variability in the times at which the sowing rains commence. However, the crop varieties that are suitable for cropping patterns differ significantly. They are associated more with soil type, and the duration of wet and dry spells within the effective rainy period.

The classification of 190 locations in India, Senegal and Upper Volta using numerical taxonomic analysis was based on a data matrix of 7 principal coordinates (derived basically from the 8 agroclimatic variables and 3 dissimilarity variables through principal coordinate analysis) and a standard Euclidean metric - unweighted pair group method using arithmetic averages (UPGMA) fusion strategy. Some rearrangement of the final groupings has been necessary to make these groups more meaningful

agronomically. With the given classification structure it is easy to add new locations without further numerical analysis.

The application of the above procedure to an independent data set from tropical Australia, suggests that the procedures developed in this study for the derivation of agroclimatic variables, and their agronomic relevance, have more general application. Also, some of the characteristics in tropical Australia differ significantly from those of India and west Africa, even though the scatter of different parameters presents nearly similar patterns over different continents. For example, wet spells exceed dry spells in northern Australia; under the same mean annual rainfall the effective rainy period is shorter in tropical Australia; the wet spells under the same effective rainy period are similar to those in India, but dry spells are far shorter in duration than those in India. Both the commencement and cessation times of effective rains show higher variability. Consequently, the dependability of crop production in tropical Australia is relatively low.

Finally, the SAT\* of India, Senegal, Upper Volta and Australia are divided into agronomically relevant homogeneous zones. Each of these zones has been analysed in terms of constraints and possible farming systems.

Methods for estimation of pan evaporation and/or potential evapotranspiration using averages and a review of the numerical taxonomic procedures, discussing the merits and demerits along with their limitations with reference to numerical continuous data sets are also presented.

This study, therefore, highlights those climatic limitations that relate to farming systems practices in India, Senegal, Upper Volta and tropical Australia. The suggested procedure thereby facilitates the transfer of well tested dry-land technology relating to farming system practices from one location to other similar locations within the semi-arid tropics. For application of the suggested procedure to areas other than the semi-arid tropics some of the criteria and assumptions used in the derivation of different agroclimatic variables need further testing or suitable modifications. The characterization of climatic fluctuations <sup>[long term systematic variations of climate]</sup> must be considered in interpreting the results relevant to farming systems. This is especially true in southern Hemisphere locations where such fluctuations are quite marked.

---

\* SAT = Semi-arid tropics



## TABLE OF CONTENTS

Declaration	ii
Acknowledgements	iii
Abstract	iv
1. INTRODUCTION	1
1.1 OBJECTIVE	1
1.2 BACKGROUND	2
1.3 SCOPE	4
2. CLIMATIC CLASSIFICATION: THE SEMI-ARID TROPICS AND THEIR ENVIRONMENT	6
2.1 INTRODUCTION	6
2.2 TROPICS	10
2.3 SEMI-ARID ZONE	10
2.3.1 Troll's approach [Troll, 1965]	10
2.3.2 Hargreaves' approach [Hargreaves, 1971]	19
2.3.3 Modified Thornthwaite's approach [Readdy & Readdy, 1973]	21
2.4 THE ENVIRONMENT OF THE SEMI-ARID TROPICS [SAT]	21
2.4.1 Climate	24
2.4.1.1 General	24
2.4.1.2 Rainfall	24
2.4.1.3 Radiation, temperature and relative humidity	27
2.4.1.4 Potential evapotranspiration	27
2.4.2 Soils	29
2.4.2.1 Soil types	29
2.4.2.2 Soil characteristics	30
2.4.3 Farming systems	31
2.4.3.1 Cultivation systems	31
2.4.3.2 Crops and cropping systems	31
2.4.4 Land and water management	33
2.4.5 Discussion	34
2.5 SUMMARY	35
3. AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS: I. A METHOD FOR THE COMPUTATION OF CLASSIFICATORY VARIABLES	37
3.1 INTRODUCTION	37
3.2 METHODOLOGY	40
3.2.1 Input data	42
3.2.2 Estimation of variables	42
3.2.3 Variables and their agronomic implications	45
3.3 COMPARATIVE ANALYSIS	47
3.4 SUMMARY	52
4. AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS: II. IDENTIFICATION OF CLASSIFICATORY VARIABLES	54
4.1 INTRODUCTION	54
4.2 DATA AND ANALYSIS	54

4.3	CROP PRODUCTION POTENTIAL [INDIA]	55
4.3.1	Spatial distribution of agroclimatic variables	55
4.3.2	Dry-seeding feasibility zones	61
4.3.3	Water-logging zones	62
4.3.4	Risk in agricultural production	62
4.3.5	Production parameters	62
4.4	COMPARATIVE ANALYSIS [INDIA, SENEGAL AND UPPER VOLTA]	63
4.4.1	Zones with similar mean annual rainfall	63
4.4.1.1	Local and regional differences	63
4.4.1.2	Regional and continental differences	65
4.4.2	Interrelationships between different variables	67
4.4.3	Dissimilarity parameters	73
4.5	SUMMARY	74
5.	AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS: III. CHARACTERISTICS OF VARIABLES RELEVANT TO CROP PRODUCTION POTENTIAL	76
5.1	INTRODUCTION	76
5.2	METHOD AND ANALYSIS	77
5.3	SOIL-WATER BALANCE SIMULATION RESULTS [INDIA]	79
5.4	COMPARATIVE STUDY	89
5.4.1	Aridisols	89
5.4.2	Alfisols	94
5.4.3	Alluvial soils (entisols)	97
5.4.4	Vertisils	98
5.5	INTEGRATION OF AGROCLIMATIC VARIABLES WITH FARMING SYSTEMS	101
5.6	SUMMARY	105
6.	AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS: IV. CLASSIFICATION OF INDIA, SENEGAL AND UPPER VOLTA	107
6.1	INTRODUCTION	107
6.2	METHODOLOGY - NUMERICAL TAXONOMIC PROCEDURES	108
6.2.1	Merits and demerits of graphical and numerical procedures	110
6.2.2	Similarity measures for continuous numerical data sets	111
6.2.3	Applicability of numerical techniques for agroclimatic classification	112
6.2.3.1	Ordination	112
6.2.3.2	Cluster techniques	112
6.3	DATA AND ANALYSIS	114
6.4	RESULTS OF NUMERICAL ANALYSIS	115
6.4.1	Principal coordinate results	115
6.4.2	Minimum spanning tree results	115
6.4.3	Cluster results	115
6.5	BASIC CRITERIA FOR THE AGROCLIMATIC CLASSIFICATION	133
6.6	COMPARATIVE STUDY OF GROUPS IN TABLE 6-4 AND FIGURE 6-6	138
6.7	CLASSIFICATION OF ZONES IN INDIA, SENEGAL AND UPPER VOLTA	141
6.7.1	Arid zone	141
6.7.2	Semi-arid zone	141
6.7.2.1	Highly undependable zone [HU]	141

6.7.2.2	Undependable zone [UD]	142
6.7.2.3	Dependable zone [DP]	144
6.7.2.4	Moderately dependable zone [MD]	145
6.7.2.5	Highly dependable zone [HD]	146
6.7.3	Sub-humid zone	147
6.7.4	General comment	148
6.8	SUMMARY	151
7.	AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS: V. CLASSIFICATION OF TROPICAL AUSTRALIA	154
7.1	INTRODUCTION	154
7.2	DATA AND ANALYSIS	155
7.3	COMPARATIVE STUDY OF AGROCLIMATIC VARIABLES	156
7.3.1	Spatial distribution of production parameters	156
7.3.2	Interrelationships among variables	163
7.4	SOIL WATER BALANCE SIMULATION RESULTS	165
7.4.1	Comparison between northern parts and Queensland	165
7.4.2	Comparison between arid and semi-arid locations in the Northern Parts	171
7.4.3	Comparisons between different parts of Queensland	174
7.5	CLASSIFICATION OF TROPICAL AUSTRALIA	180
7.5.1	Arid zone	181
7.5.2	Semi-arid zone	184
7.5.3	Sub-humid zone	187
7.6	SUMMARY	187
8.	CONCLUSIONS AND SUGGESTIONS	192
8.1	INTRODUCTION	192
8.2	DEMARCATON OF THE SEMI-ARID TROPICS [SAT]	192
8.3	AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS [SAT]	193
8.3.1	Method for the derivation of classificatory variables	193
8.3.2	Dissimilarities in the pattern of agroclimatic variables	194
8.3.3	Characterization of production parameters	195
8.3.4	Agroclimatic classification	196
8.4	SUGGESTED FUTURE AREAS OF RESEARCH	199
	BIBLIOGRAPHY	201
	Appendix A. CLIMATIC CLASSIFICATION PROCEDURES	220
	Appendix B. SECONDARY REFERENCES	221
	Appendix C. THE STANDARD WEEKS	222
	Appendix D. LIST OF RAINFALL STATIONS FOR WHICH THE ANALYSIS WAS MADE	223
	Appendix E. COMPUTATIONAL DETAILS OF POTENTIAL EVAPOTRANSPIRATION [PE]	225
	Appendix F. NUMERICAL TAXONOMIC PROCEDURES - a review	232



## LIST OF FIGURES

Figure 2-1:	World semi-arid tropics [Troll, 1965]	11
Figure 2-2:	SAT map of Africa, India, Brazil and Australia [Revised Troll's approach]	14
Figure 2-3:	Rice, pearl millet and sorghum cropping regions in India	17
Figure 2-4:	SAT map of Thailand [a] Revised Troll's approach [b] Modified Thornthwaite's approach	18
Figure 2-5:	SAT map of Africa, India and Brazil [Hargreaves' approach]	20
Figure 2-6:	SAT map of Africa, India, Brazil and Australia [Modified Thornthwaite's approach]	22
Figure 2-7:	Seasonal distribution of rainfall and PE for 12 selected locations in the SAT	25
Figure 2-8:	Observed and estimated seasonal trend in mean annual rainfall [Mahalapye, Botswana]	26
Figure 3-1:	[a] Agricultural subdivisions and length of growing season [b] Predominant soil types	39
Figure 3-2:	Computation of PS, S, G, W, and D [hypothetical case for one year]	41
Figure 4-1:	Location of selected stations in India	56
Figure 4-2:	Location of selected stations in Senegal and Upper Volta	57
Figure 4-3:	Spatial distribution of agroclimatic attributes	58
Figure 4-4:	Spatial distribution of the percentage crop failure years or percentage years with $G \leq 5$ weeks [A]	60
Figure 4-5:	Variation of the average effective rainy period [G] with the coefficient of variation of the effective rainy period [C] for India, Senegal and Upper Volta	68
Figure 4-6:	Variation of the average effective rainy period [ $\bar{G}$ ] with the average wet [ $\bar{W}$ ] and dry [ $\bar{D}$ ] spells within the effective rainy period in India, Senegal and Upper Volta	69
Figure 4-7:	Variation of the average wet spells [ $\bar{W}$ ] with the average dry spells [ $\bar{D}$ ] within the effective rainy period for India, Senegal and Upper Volta	71
Figure 4-8:	Variation of the coefficient of G [C] with the standard deviation of S [ $\delta$ ] for India, Senegal and Upper Volta	72
Figure 5-1:	Comparison of observed and predicted dry matter and grain yields [years: 1979 and 1980; seasons: kharif and rabi; sorghum cultivars: CSH1, CSH6, CSH8, M-35-1 and SPV-351]	78
Figure 5-2:	Soil water balance results of Jodhpur	81
Figure 5-3:	Soil water balance results of Anantapur	82
Figure 5-4:	Soil water balance results of Bangalore	85
Figure 5-5:	Soil water balance results of Hyderabad	85
Figure 5-6:	Soil water balance results of Sholapur	87
Figure 5-7:	Soil water balance results of Akola	88
Figure 5-8:	Soil water balance results of Indore	90
Figure 5-9:	Graphical presentation of agroclimatic variables together with recommended cropping patterns at selected locations in India	102

Figure 6-1:	Flow chart of agroclimatic classification	109
Figure 6-2:	Results of principal coordinate analysis [coordinates 1 versus 2, 1 versus 3 and 2 versus 3]	117
Figure 6-3:	Minimum spanning tree [MST]	118
Figure 6-4:	Dendrogram of different fusion strategies with standardized Euclidean metric [limited to 30 groups]	119
Figure 6-5:	Dendrograms of different fusion strategies with Gower metric [limited to 30 group]	120
Figure 6-6:	Dendrogram estimated following group average fusion strategy with Euclidean metric	121
Figure 6-7:	Dendrogram depicting the results of numerical analysis	122
Figure 6-8:	Main branches and associated average pattern of agroclimatic attributes [Fig. 6-6]	125
Figure 6-9:	Branch 2 and associated groups along with the average pattern of agroclimatic attributes [Fig. 6-8]	126
Figure 6-10:	Branch 5 and associated groups along with the average pattern of agroclimatic attributes [Fig. 6-8]	127
Figure 6-11:	Branch 6 and associated groups along with the average pattern of agroclimatic attributes [Fig 6-8]	128
Figure 6-12:	Branch 9 and associated groups along with the average pattern of agroclimatic attributes [Fig. 6-8]	129
Figure 6-13:	Branch 7 and associated groups along with the average pattern of agroclimatic attributes [Fig. 6-8]	130
Figure 6-14:	Branch 8 and associated groups along with the average pattern of agroclimatic attributes [Fig. 6-8]	131
Figure 6-15:	Agroclimatic classification of India	149
Figure 6-16:	Agroclimatic classification of Senegal and Upper Volta	150
Figure 7-1:	Location of selected stations in tropical Australia	157
Figure 7-2:	Spatial distribution of the mean week of commencement time of sowing rains $\langle \bar{S} \rangle$ , week number	158
Figure 7-3:	Spatial distribution of the standard deviation of the commencement time of sowing rains $\langle \delta \rangle$ , weeks	158
Figure 7-4:	Spatial distribution of the average available effective rainy period $\langle \bar{G} \rangle$ , weeks	159
Figure 7-5:	Spatial distribution of the coefficient of variation of the effective rainy period [C], %	159
Figure 7-6:	Spatial distribution of the average wet spells within the effective rainy period $\langle \bar{W} \rangle$ , weeks	160
Figure 7-7:	Spatial distribution of the standard deviation of the wet spells $\langle \alpha \rangle$ , weeks	160
Figure 7-8:	Spatial distribution of the average dry spells within the effective rainy period $\langle \bar{D} \rangle$ , weeks	161
Figure 7-9:	Spatial distribution of the standard deviation of the dry spells $\langle \beta \rangle$ , weeks	161
Figure 7-10:	Spatial distribution of the percentage crop failure years [G < 5 weeks] [A], %	162
Figure 7-11:	Variation of C versus $\bar{G}$ ; $\bar{W}$ and $\bar{D}$ versus $\bar{G}$ ; $\bar{D}$ versus $\bar{W}$ and $\delta$ versus C over tropical Australia	166
Figure 7-12:	Soil water balance simulation results for Katherine under three soil types [K = 50, 100 and 200 mm]	168
Figure 7-13:	Soil water balance simulation results for Townsville under three soil types [K = 50, 100 and 200 mm]	169
Figure 7-14:	Variation of sorghum yields with the effective rainy period at Katherine	172

Figure 7-15:	Soil water balance simulation results for Pine Creek, Argyle Downs and Derby under deep black soils [K = 200 mm]	175
Figure 7-16:	Soil water balance simulation results for Atherton and Mt Surprise under deep black soils [K = 200 mm]	177
Figure 7-17:	Soil water balance simulation results for Woodstock and Clermont under deep black soils [K = 200 mm]	178
Figure 7-18:	Soil water balance simulation results for Marlborough and Mitchell under deep black soils [K = 200 mm]	179
Figure 7-19:	Agroclimatic classification of semi-arid tropical Australia	183
Figure 7-20:	Soil water balance simulation results of two Niger locations [Niamey Ville and Maradi] in west Africa	188
Figure F-1:	Geometric presentation of similarity measures	237
Figure F-2:	Presentation of the 11 locations in the first three principal coordinates or components	247
Figure F-3:	Graphical representation of different fusion strategies of clustering	251
Figure F-4:	Dendrogram of different fusion strategies with different similarity metric and data matrices	255



## LIST OF TABLES

Table 2-1:	Details of different approaches for demarcating the SAT	12
Table 2-2:	Data base and data source	15
Table 2-3:	Percentage area under the SAT according to modified Thornthwaite's and Troll's approaches	23
Table 2-4:	Seasonal variation of temperature and relative humidity in world SAT	28
Table 3-1:	Climatic classification results based on the present [R-method] approach	48
Table 3-2:	Climatic classification results based on various approaches	50
Table 3-3:	Climatic attributes and percentage area under kharif [rainy season] fallow for selected locations in the deep vertisol regions of India	51
Table 4-1:	Climatic attributes for selected locations in India [dependable and undependable rainfall areas]	64
Table 4-2:	Climatic attributes for selected locations in India, Senegal and Upper Volta	66
Table 5-1:	Success of different crops in rainy and post-rainy seasons at few selected locations in India -- based on soil water balance simulation	86
Table 5-2:	Cropping pattern performance results at (a) Anantapur, (b) Sholapur, (c) Akola, (d) Indore and (e) Dholi in India	91
Table 6-1:	Contribution of different attributes expressed as correlation coefficient to the first 7 principal coordinates	116
Table 6-2:	Location numbers of different groups in Figs. 6-8 to 6-14	132
Table 6-3:	Basic criteria for the sub-division of regions into zones and sub-zones	134
Table 6-4:	Agroclimatic classification results [India, Senegal & Upper Volta]	136
Table 7-1:	Climatic attributes for few selected locations in tropical Australia	164
Table 7-2:	Variation of wet and dry spells under different effective rainy periods in different countries [based on Figures 4-6 and 7-11]	167
Table 7-3:	Yield potential at Katherine	173
Table 7-4:	Agroclimatic classification results [tropical Australia]	182
Table F-1:	Data matrix representing 11 locations with 11 attributes	235
Table F-2:	Different forms of distance measures	239
Table F-3:	Similarity matrices for different similarity measures with different standardization procedures using the data presented in Table F-1	242
Table F-4:	Hierarchical agglomerative-polythetic fusion strategies expressed as flexible strategy of Lance & Williams	252
Table F-5:	Coefficients of comparison between different fusion strategies using different similarity matrices with different types of attributes	257

## CHAPTER 1

### INTRODUCTION

#### 1.1 OBJECTIVE

The broad objective of this study is to identify the climatic limitations that relate to farming systems and to classify the regions according to these limitations with reference to the semi-arid tropics (hereafter referred to as SAT). The specific objective is to identify a suitable package of farming systems procedures and the level of associated risk in order to facilitate the transfer of location-specific farming systems technology within the SAT.

To achieve this objective the study is divided into two sections: (i) Identification of the SAT; and (ii) sub-division of the SAT into agronomically relevant homogeneous zones. The first presents broad climatic patterns of the world (Chang, 1981) and the second objective presents the agroclimatic classification (Slatyer, 1975).

To study and compare the climatic variations relevant to crop production systems it is first necessary to identify agronomic variables that relate to dry-land crop production systems, such as:

- what is the optimum time for sowing?
- what is the appropriate crop and cropping pattern in that environment?
- is dry-seeding feasible in heavy soils?
- is runoff recycling feasible?
- are there sufficient field working days for cultural operations?
- is land management an important factor?
- what is the level of risk with the dry-land agriculture?

The agroclimatic variables that are derived from such questions are

not only useful factors in the transfer of dry-land technology but aid in integrating those aspects of climate which affect agricultural production. This study, therefore, not only involves identification of suitable data sets but also identification of suitable methods for the estimation of agroclimatic variables and characterization of their agronomic relevance.

Secondly, agroclimatic classification involves the identification of a suitable method for grouping of locations according to their agronomic relevance.

The process of classification, therefore, involves a number of discrete steps, such as:

- establishment and standardization of data matrix;
- identification of suitable methods for the demarcation of the SAT;
- identification or development of suitable methods for the derivation of agroclimatic variables;
- characterization of identified agroclimatic variables with agronomic data;
- identification of suitable procedures for grouping of the locations according to their agronomic relevance;
- testing the procedure with an independent data set;
- interpretation of final results.

I carried out a climatic classification study with reference to data sets from India & Thailand in Asia; Africa; Brazil in south America; and Australia. In the agroclimatic classification study data for India, two west African countries (Senegal and Upper Volta) and tropical Australia have been used. The data from the first three countries have been used in the development of principles while the data from Australia have been used in testing the validity of the procedures.

## 1.2 BACKGROUND

The concept of agroclimatology existed long before its precise formulation (Theile, 1895). The term "agricultural climatology" has been in use in English since 1920 (Smith, 1920), in German since 1930



(Holdfless, 1930) and in Russian since 1937 (Selianinov, 1937). Burgos (1958) defined agroclimate as "the total of climatic conditions rendering possible economic cultivation of species, expressed either in their values of intensity, duration, frequency and movement of occurrence, or in values of ~~their~~ <sup>other</sup> integral effects upon living organisms and the soil".

The application of <sup>agronomatology and</sup> agroclimatology becomes more useful when the dynamics of agricultural production as a function of weather and climate are better understood. Variables in the two fields, climatic and agronomic, exist on all scales of space and time, i.e., micro, local, regional and global. For the application of agroclimatology to agricultural production to be meaningful much effort will have to be made in both disciplines in order to define the limiting factors. In the case of agriculture, one can analyse the actual agricultural process and identify the limiting factors in the production cycle; and in the case of climate, one can analyse the meteorological conditions of a region and relate them to the production systems.

Traditional crop production systems of the farmer often do not make full and efficient use of available soil and water resources. Their crops, varieties and cropping systems are often complex and finely attuned to the prevailing biophysical and socio-economic environment. Such systems are remarkably homeostatic in that yields remain stable, but low. The objective of the farmer is to minimize year-to-year variation rather than maximize profit (Nix, 1981). To improve this situation, new techniques for resource management which more effectively conserve and utilize the rainfall<sup>\*</sup> and the soil, and new crop production systems which increase productivity and minimize instability in crop production need to be developed. One such possibility is through the transfer of farming systems technology (package of principles) to other locations having a similar physical environment to that of the experimental station, where the principles were developed and/or tested. <sup>Such work</sup> ~~This~~ involves the establishment of guiding parameters for the transfer of such location-specific farming system technology to other regions.

A logical step in improving the crop production systems, is therefore, to understand and quantify the climates of different regions and classify them into agronomically relevant homogeneous zones. Several publications have appeared in the literature in recent years on this subject (Mather, 1978), although, in the case of the dry tropics, methodologies

\* In the SAT crop production per unit area is farming system-specific, and, in turn, farming systems are climate, particularly rainfall, - specific.

(Thornthwaite & Mather, 1955; Troll, 1965; Hargreaves, 1971) to date have not helped much in the transfer of technology. Mather (1978) discussed the general climate-soil-vegetation of the world, but the dry tropics, i.e., regions with moisture index ( $I_m$ ) ranging from 20 to -100% with potential evapotranspiration ranging from 1400 to 2500 mm or more, received little attention. The humid and more reliable rainfall areas have been extensively and intensively cultivated and heavily populated by human beings. The opportunity for expansion now lies in the dry lands of the semi-arid zone. These lands are mostly confined to the tropics especially in developing countries with high population pressure. There is a well recognised and urgent need for the development of dry farming technology for increasing agricultural production to meet the increasing demand placed on these lands by ever increasing population pressure (Kanwar, 1975). Also, divergent statements about tropical climates in the literature (Troll, 1965; Gray, 1970; Hargreaves, 1971) seem to call for clear definitions of the characteristics and variability of these climates in relation to agricultural production. Many misconceptions (e.g., what is semi-arid, where they lie etc.) arise because the tropical climates range from extreme deserts to evergreen rain forests. **The present study is directed mainly towards semi-arid areas in the tropics.**

### 1.3 SCOPE

The delineation of climatological regions by scientists originated almost simultaneously with that of determining biological regions (Boyko, 1962). The need for a holistic and systematic approach to problems of very complex systems such as crop production systems, has long been recognized (Supan, 1884; Hult, 1892), but, until recently the conceptual and computational tools needed were not developed (Nix, 1981). Any agroclimatic classification is variable-dependent, however, and the choice of variables will influence the classification obtained. The variables used to divide the semi-arid tropics into relevant agronomically homogeneous zones should define climatic limitations that relate to land and water management, and crop and cropping system practices, and the risk associated with the dry-land agriculture. Such variables play a major role in the transfer of location-specific technology to other regions.

Swindale (1979) has reported that according to Nix (1968, 1979) that there are three different, but not mutually exclusive, approaches to

predict the success of the transfer of site-specific agricultural technology. These three approaches represent different ways of defining agroclimatic variables:

- **analogue transfer**, whereby areas analogous to the experimental site are identified by soil and/or climatic classifications;
- **site-factor methods**, which by following multiple linear regression techniques, enable a researcher to relate key climatic parameters to biological productivity within a given environment. These are location-specific and, therefore, are of little use in the transfer of technology;
- **simulation techniques**, using crop weather models, which allow the development, combination and utilization of physical laws that govern biological processes. Inherently the crop-weather models should be the most efficient methods for overcoming site-factor constraints.

Despite intensive research on individual components and processes, the entire crop production system is not well understood (Nix, 1981). SORGF (a dynamic sorghum growth development) model of Arkin et al. (1976) which was developed under sub-humid, extra-tropical conditions needs considerable modification for its useful application under semi-arid tropical conditions. This is still more complicated by the divergent behaviour of different genotypes of the same crop to weather (Reddy et al., 1984a). Furthermore, the performance of different crops/varieties under mixed cropping are quite different from that of single crops; yield advantages of different crop combinations are less quantified till now. Crop mixtures provide one of the major cropping patterns in the semi-arid tropics. Therefore, unless the whole mechanism of crop-weather is understood clearly, the empirical equations built on few experimental results, by not considering the farmer's field conditions, may not produce reliable results. However, a great many partial models of important components and sub-systems have been developed (Arkin et al. 1976; Reddy, 1983a). Given the above situation, the logical approach to adopt is analogue transfer, and this has been followed in the present study.

## CHAPTER 2

### CLIMATIC CLASSIFICATION: THE SEMI-ARID TROPICS AND THEIR ENVIRONMENT

#### 2.1 INTRODUCTION

The objective of this chapter is to clarify usage of the term "semi-arid tropics" and to develop a more explicit definition. This involves the establishment of relevant physical environmental characteristics for the identification of homoclimes, zones of comparable climates. The purpose of climatic classification is to identify those aspects of climate which distinguish a region from nearby regions and to derive inferences about the influence of climatic factors on human, animal and plant life. In an environmental context this may allow areas to be characterized and boundaries to be drawn around contiguous areas that can be regarded as homogeneous in certain respects.

In dividing the world into a number of "climatic types" there is a certain artificiality in the establishment of their boundaries. This is because boundaries are shown as sharp delineations, whereas actually there is a gradual transition in the climate. For a general climatic classification to be realistic, boundaries should at least conform with known plant distribution boundaries (Wilsie & Shaw, 1954). Good (1953) states that the facts of plant geography everywhere show that plant distribution is basically dependent on climate. Edaphic factors are secondary, because they are often controlled by climatic factors. Thus, climatic factors will determine whether corn shall be a potential occupant of a given area, whereas terrain and soil factors may determine largely whether corn actually will be grown and in what abundance (Wilsie & Shaw, 1954).

Climatic differences between various regions were recognized by the Greeks as early as 600 B.C. (Boyko, 1962). The importance of climatic classification was generally recognized by the middle of the present century. There exists in the literature (Boyko, 1962; Burgos, 1968) a wide spectrum of approaches for climatic zonation. In 1735 Reaumur developed a thermal index. Supan (1884) and Hult (1892) presented the

review of the work in that century and indicated that the climatic classifications were developed arbitrarily, lacked precision and use political and geographical zones.

Most of these models were based on annual temperature and natural vegetation distribution. Prior to the present century, the work was mostly being carried out by National Organizations and Educational Institutes only. From the beginning of the present century the work was also being carried out by International Organizations (Burgos, 1968). However, the suitability of individual methods depends upon the problem that is envisaged and the availability of input data. The purpose of classification in the present context is to identify the semi-arid areas especially in the tropics as this will facilitate the subdivision of these regions into agronomically homogeneous zones that offer guidance in the transfer of site-specific dry-land technology.

As the interest here is directed towards agriculture in tropical areas, climates of these regions can be divided into a finite number of groups, such as arid, semi-arid, sub-humid or wet-dry, humid etc., in an orderly fashion on a broad scale (from a drier extreme to wetter extreme) on the basis of land use systems. The arid zone towards the drier extreme of climates represent the grasslands where food crop production is uneconomical under unirrigated conditions; and the other extreme, representing rain forests, is termed the humid zone. In between these two extremes the major food crop zones of the tropics can be divided into two parts, namely the semi-arid zone towards the drier side and the sub-humid towards the wetter side. On the wetter side dry-land agriculture is risky due to heavy rains and some of the food crops of this region are paddy-rice, sugarcane, finger millet etc. (under rainfed condition). The semi-arid lands are the major dry-land agricultural zone and some of the major food crops of this region are pearl millet, sorghum, pigeonpea and groundnut etc. (under rainfed conditions). For food crop production a shortage of soil moisture is the limiting factor under rainfed conditions in the arid and semi-arid zones while excessive rains are the major constraint in sub-humid and humid zones. Hence, the mechanisms and limiting factors for agricultural production are different in these two areas.

There is ambiguity both in the usage of the term "semi-arid" and its implied practical application. This ambiguity stems from: (1) the method of defining broad zones; both in terms of the choice of climatic

parameters that are used to define an index and the class limits of the index; (2) the association of defined zones with specific natural vegetation formations and/or land use systems.

The literature is rich in papers that present the spatial distribution of single climatic parameters such as rainfall, evaporation, temperature, radiation, wind and humidity. However, no single parameter can reflect the climate of a place. The majority of useful classifications use two primary factors to define climate, namely moisture, which limits the plant growth, and evaporative demand, which expresses the moisture need at a place for optimum plant growth. Very few classifications use general weather conditions in defining climate. Two broad modes of defining "semi-arid" in terms of moisture and evaporative demand are seen in the literature. They are annual indices and duration of moist or dry period. Some of these are presented in Appendix A.

Most of the commonly used procedures adopt annual indices (Köppen, 1936; Thornthwaite, 1948; Thornthwaite & Mather, 1955; Budyko, 1956; Papadakis, 1975). The procedures that use the moist or dry period are those of Schreiber (1975); Cocheme & Franquin (1967); Brown & Cocheme (1968); Raman & Murthy (1971); Troll (1965); Hargreaves (1971). However, only the last two methods are used to demarcate the semi-arid zone.

Those approaches with temperature as the threshold limit use natural vegetation as the reference in the demarcation of broader zones. According to Meher-Homji (1962), when some of these procedures are applied to 78 representative stations of the Indian subcontinent, none of these procedures give entirely satisfactory results in classifying all the stations according to their vegetation types. In the broader zonation the approaches with potential evapotranspiration (or its equivalents) as the threshold limit used food crops or natural vegetation as a reference. However, the internal homogeneity of the majority of these methods, even on a broader scale, is low (Reddy, 1977a). This is basically because the procedures lack the objectivity and some are derived on the basis of regional studies or the application of already existing models to <sup>the</sup> that environment <sup>under study</sup> with minor modifications. For example, the zones were defined with reference to vegetation types of west Africa by Troll (1965) and in terms of food crop production over NE Brazil by Hargreaves (1971).

The past century has witnessed the introduction and evolution of

ideas that have successfully brought greater precision and objectivity to climatic classifications. In Köppen's (1936) classification the zones can show vast variations within themselves (Berry et al., 1973; Hashemi et al., 1981). In this method temperature was used as a proxy for evaporation, but evaporation is not only a function of temperature but also of several other climatic factors (Penman, 1948). With Köppen's monumental study the way was opened for analogue climatic classifications and many others followed as a result. Thornthwaite's (1948) climatic classification introduces the most important term potential evapotranspiration and also the degree of moisture of climatic units by means of an estimate of soil-water balance. The latter was subsequently modified by Thornthwaite & Mather (1955). While the main emphasis of Köppen's classification is on temperature limits, Thornthwaite's climatic classes are based on the effectiveness of precipitation. This factor bears a close relation to plant growth and hence permits more refined analysis of climatic problems related to vegetation and agriculture than does the Köppen scheme (Berry et al., 1973). In the Thornthwaite approach, however, arbitrarily chosen intervals were used in the division of humid and dry areas. These limits are not homogeneous with respect to crop production areas. Also, unequal weightings were given to humid and arid indices in the computation of moisture index which is not justified by the authors. Thornthwaite also introduces a soil moisture factor (which was also used by others later: Papadakis, 1975; Eagleman, 1976), which is not realistic, as there are wide variations in soil factors even at a micro-level. In fact, the moisture index computed with and without a soil factor doesn't show any significant difference under dry climates. Hargreaves (1974) states that "a composite index based upon soil and climate might be developed. However, due to the complexity of soils in many areas such a combined index might be difficult to use in agroclimatic zonation". Reddy & Reddy (1973) suggested some modifications to Thornthwaite's scheme to develop more homogeneous types (hereafter referred to as "modified Thornthwaite's approach"). In this system the soil term was eliminated in the computation of moisture index; the same weights were given both for humid and arid indices; and uniform limits were used on both humid and dry sides of the scale.

As shown in the above discussion the following three methods are found appropriate to demarcate the semi-arid zone. They are:



1. Troll's humid period:
2. Hargreaves' dependable moist period:
3. Modified Thornthwaite's annual moisture index.

Table 2-1 presents the details of these three methods. Monthly and annual data from India, Africa, Brazil, Australia and Thailand representing a wide range of climatic regimes are used (Table 2-2) to test the above three methods. This chapter also briefly presents some of the general features of the semi-arid tropical environment.

## 2.2 TROPICS

In order to determine the semi-arid tropics we must first define the tropics. The SAT is then a component of the tropical environment.

In the astronomical sense the tropics refer to the region between the  $23^{\circ} 27'$  North and South Parallels. However, in climatological and meteorological studies thermic units in terms of mean annual temperature are preferred for defining the tropics (Koppen, 1936; Hargreaves, 1974). Also plant species react to temperature rather than to latitude (which defines the photoperiod) as such. Photoperiod influences development while temperature affects both growth and development of plants. Although there are many proposed definitions, that of Koppen (1936) is simple and reasonable (Reddy, 1977a). Accordingly, the tropics are thermally defined as regions with mean annual temperature  $\geq 18^{\circ}\text{C}$ . This limit was accepted at a consultant meeting on climatic classification held at ICRISAT during 14-16 April, 1980 (details can be seen from the proceedings). This limit is the lower optimum value of the temperature for optimum growth of dry-land crops and below which the retardation of growth is considerable.

## 2.3 SEMI-ARID ZONE

### 2.3.1 Troll's approach [Troll, 1965]

As adopted by Gray [1970]: ICRISAT adopted Troll's (1965) map (Fig. 2-1) as a working document to demarcate the semi-arid zone. Gray (1970) identified regions with 2-7 humid months on this map as the semi-arid zone (Table 2-1). It appears (Walter et al., 1975) that Troll defined a humid month with mean monthly rainfall ( $R$ , mm) exceeding twice the mean monthly average temperature ( $T$ ,  $^{\circ}\text{C}$ )-- $R \geq 2T$  (Table 2-1).

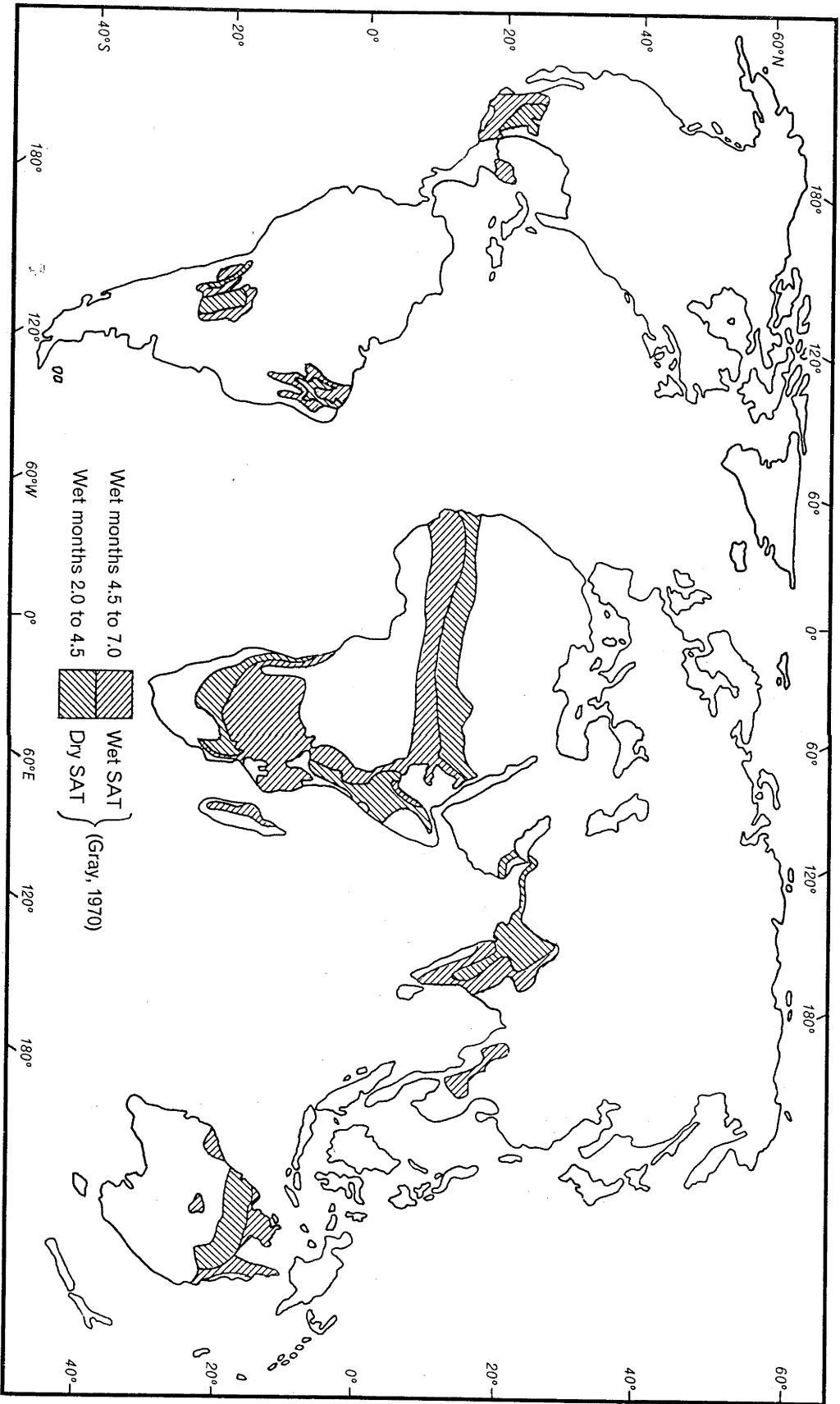


Figure 2-1 : World semi-arid tropics (Troll, 1965)-

Table 2-1 : Details of different approaches for demarcating the SAT.

Approach	Data requirement	Criteria (attribute)	Limits, Units (for the SAT)
<u>Troll's approach</u>			
Troll (1965)	Average monthly R&T	$R \geq 2T^*$	2-4.5 months
Gray (1970)	Average monthly R&T	$R \geq 2T^*$	2-7.0 months
Reddy (1977a)	Average monthly R&PE	$R \geq PE$	2-4.5 months
<u>Hargreaves approach</u>			
Hargreaves (1971)	Monthly DP and PE	MAI (DP/PE) $\geq 0.34^{**}$	3-4 consecutive months
<u>Modified Thornthwaite's approach</u>			
Reddy and Reddy (1973)	Mean annual R&PE	$I_m = \frac{(R-PE)}{PE} \times 100$	$-25 \leq I_m < -75\%$

\* It appears that Troll (1965) used Gaussen (1954) definition in defining humid month (Walter et al., 1975).

\*\* It is equal to  $R/PE \geq 0.50$  (Hargreaves, 1975), as square root of monthly rainfall generally follow normal or nearly normal distribution.  $R \geq 2T$  can also be represented approximately as  $R \geq 0.5PE$ . This is half the limit used by Reddy (1977a).

R = Rainfall, mm

PE = Potential evapotranspiration, mm

DP = Dependable precipitation estimated using long period rainfall data (75% probability value), mm

T = Temperature, °C

following Gaussen (1954). That is, Troll, like Koppen, used temperature as a proxy for evaporation. In the tropics during the rainy season the average monthly temperature is about  $30^{\circ}\text{C}$ . This is equivalent to mean monthly rainfall of about 60 mm or less. During the same period, PE (potential evapotranspiration) is about 100-150 mm ( $R \geq 2T$  approximately represents  $R \geq 0.5 \text{ PE}$ ). <sup>monthly average</sup>  $\{R \geq 2T \text{ for 2-7 months}\}$  are considered as semi-arid by Gray (1970) (as Troll himself did not use the term semi-arid in his paper). Hence, large areas with mean annual rainfall less than 200 mm (for example: Northwest India, Southern parts of the Sahara desert in north Africa and drier parts of NE Brazil, South Africa and parts of inland Australia) are included under semi-arid. Also, on the wetter side the SAT includes high rainfall regions of the West Coast of India etc. with mean annual rainfall exceeding 2000 mm. This is also evident in the case of Brazil and Australia. Therefore, this approach is unacceptable as the SAT extends from regions with about 200 mm of mean annual rainfall to regions with mean annual rainfall of about 2000 mm and include vegetation formations ranging from shrub steppe and grasslands to rainforests.

**As revised by Reddy [1977a]:** To overcome some of the above mentioned deficiencies Reddy (1977a) modified the method of computing the humid period (Table 2-1). The SAT maps of India, Brazil, Africa, Australia and Thailand (Figs. 2-2 & 2-4a) are redrawn using PE estimates in place of T. A humid month is defined by  $R \geq \text{PE}$  and the zone with 2-4.5 humid months is defined as semi-arid. A description of the data used in producing these revised maps, along with data sources, are presented in Table 2-2.

**India:** The revised SAT map of India (Fig. 2-2) is based on data from about 300 locations. The monthly rainfall data are taken from an India Meteorological Department [IMD] (Undated) publication and PE data are based on data from Rao et al. (1971). However, many scientists have expressed reservations in accepting this map [At the same consultant meeting, referred to earlier, the majority of the participants expressed a need to modify this approach]. Specifically, (i) the high rainfall regions of coastal Maharashtra, Bihar, West Bengal, eastern Madhya Pradesh, Orissa etc. within the SAT have paddy-rice as the major crop (Fig. 2-3) [The extreme eastern parts below  $19^{\circ}\text{N}$  lat. represent irrigated paddy; Johnson, 1979] and (ii) elimination of the major pearl millet, sorghum, groundnut, and pigeonpea (Fig. 2-3; Easter & Abel, 1973) [The western parts above

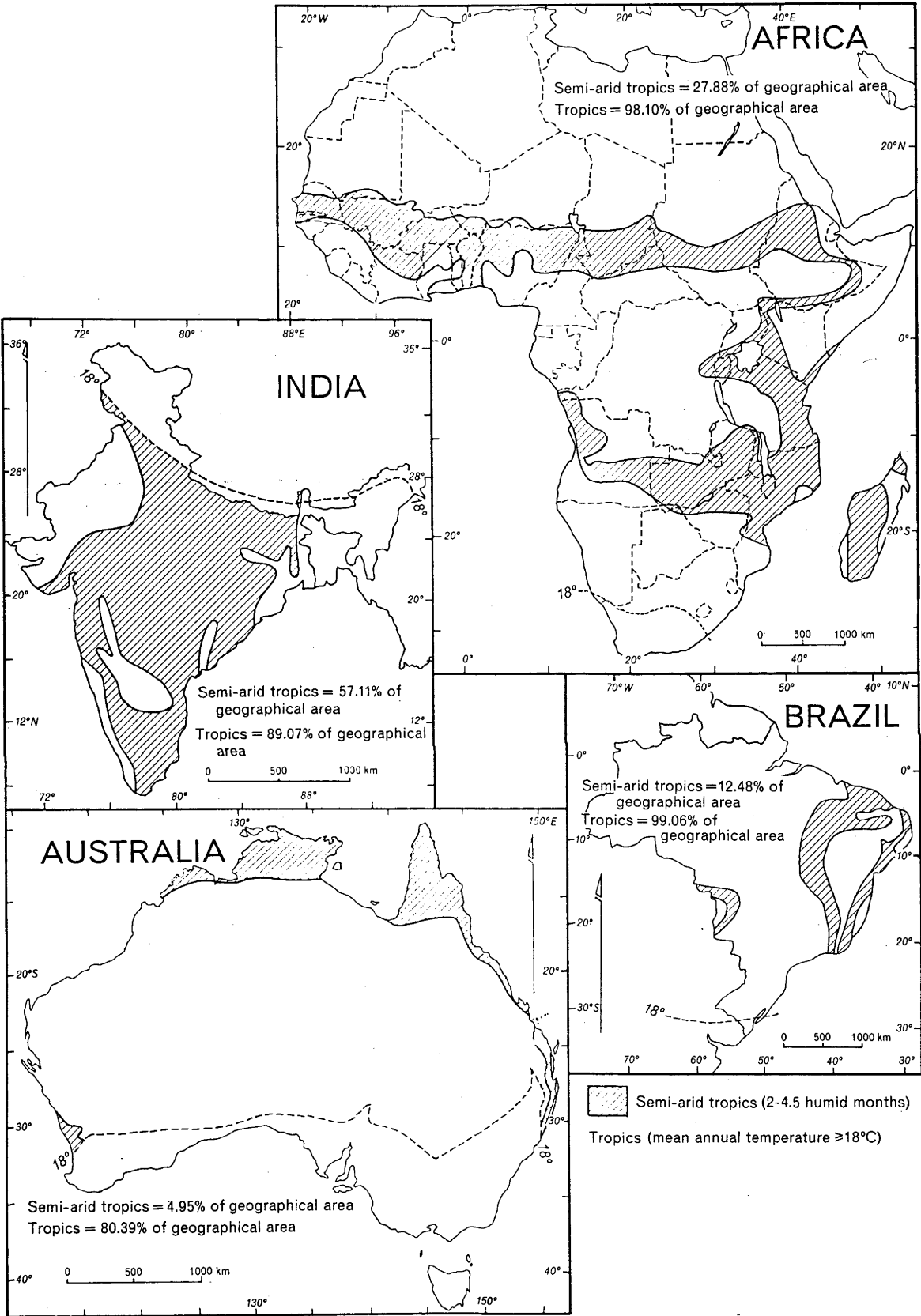


Figure 2-2 : SAT map of Africa, India, Brazil and Australia (Revised Troll's approach).

Table 2-2 : Data base and data source.

Region/Country	Data Source		Data base (no. of locations)
	Rainfall (R) *	PE	
India	IMD (Undated)	Rao et al. (1971)	300
NE Brazil	Hargreaves (1973)	Reddy (1981a)	180
Brazil (excluding NE)	Hargreaves (1977)	Hargreaves (1977)	20
West Africa (Sene- gal, Mali, Upper Volta, Niger, Chad)	Virmani et al. (1980)	Reddy & Virmani (1980a)	300
Africa (excluding West)	FAO**, WMO (1971)	FAO**, WMO (1971)	280
	Griffiths (1971)	Griffiths (1971)	
Thailand	MD (1971)	Reddy (1981b)	49
Australia	DSBM (1975)	Nix***	350

\* In the case of India, dependable precipitation (DP) data were computed using the long term rainfall data of 50 years for the same 300 locations (IMD, 1967).

\*\* Data has been supplied by Michel Frere, Senior Agrometeorologist, FAO, Rome.

\*\*\* H.A. Nix (Personal communication).

20°N lat. represent irrigated pearl millet; Johnson, 1979] growing regions from the SAT and including these within the arid zone.

Africa: Figure 2-2 also depicts the revised SAT map of Africa. R and PE data for 300 locations in Senegal, Mali, Upper Volta, Niger and Chad are taken respectively from Virmani et al. (1980) and Reddy & Virmani (1980a). For the rest of Africa for 280 locations data are partly from FAO (M. Frere, pers. comm.), and partly from Griffiths (1971) and World Meteorological Organization [WMO] (1971). Although well distributed over west Africa, data are sparse over the rest of Africa. Some of the anomalies reported above in the Indian situation are also evident in the case of Africa.

Brazil: Using data (Hargreaves, 1973, 1977; Reddy, 1981a) for about 200 locations the SAT areas are demarcated for Brazil (Fig. 2-2). In this map, not only are higher rainfall regions included under the SAT, but regions with more than 900 mm of mean annual rainfall are included within the arid zone.

Australia: Figure 2-2 depicts the revised SAT map of Australia. This map is based on data for 350 locations. Mean monthly rainfall and PE data are taken respectively from Department of Science and Bureau of Meteorology [DSBM] (1975) and H.A. Nix (pers. comm.) --PE = 0.85 E, where PE is the potential evapotranspiration and E is the open pan evaporation (Reddy, 1979a). As in India, the rainfall in the Australian SAT varied between 740 and 2050 mm (An anomaly which occurs in that part of the winter, wet/summer dry zone of southwestern Australia is included because mean temperature exceeds 18°C). In the sub-humid zone the mean annual rainfall varies between 1100 and 1900 mm. Regions with about 800 mm are included as arid while most regions with more than 1500 mm are rainforest areas or which have the rainforests been cleared.

Thailand: The revised SAT map of Thailand (Fig. 2-4a) is based on 49 locations data (Meteorological Department [MD], 1977; Reddy, 1981b).

Because of the deficiencies presented above <sup>[particularly the anomalies with reference to rainfall amount]</sup> in dry-land agriculture, the revised Troll's method is also not acceptable for the demarcation of the SAT.



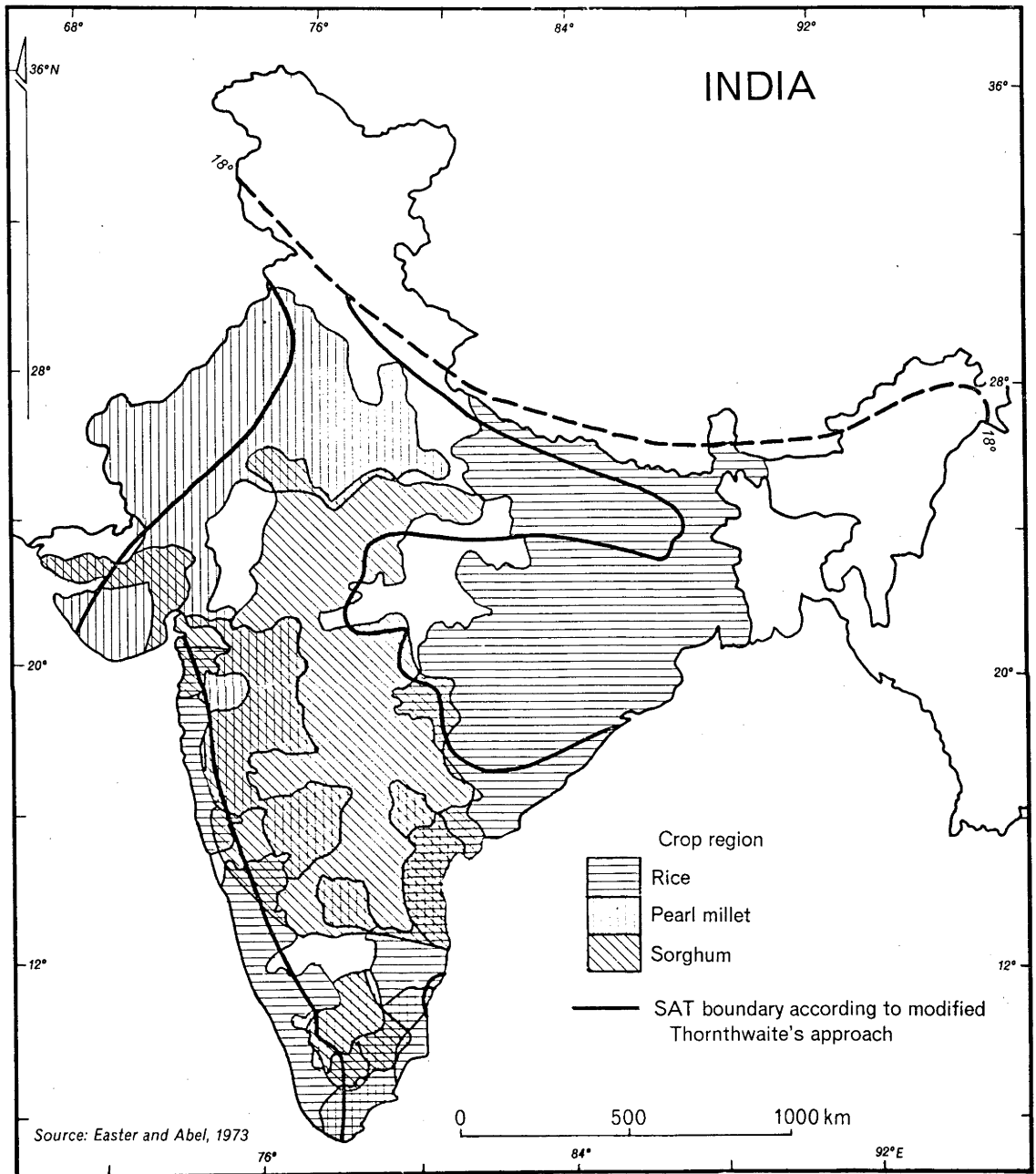


Figure 2-3 : Rice, pearl millet and sorghum cropping regions in India.

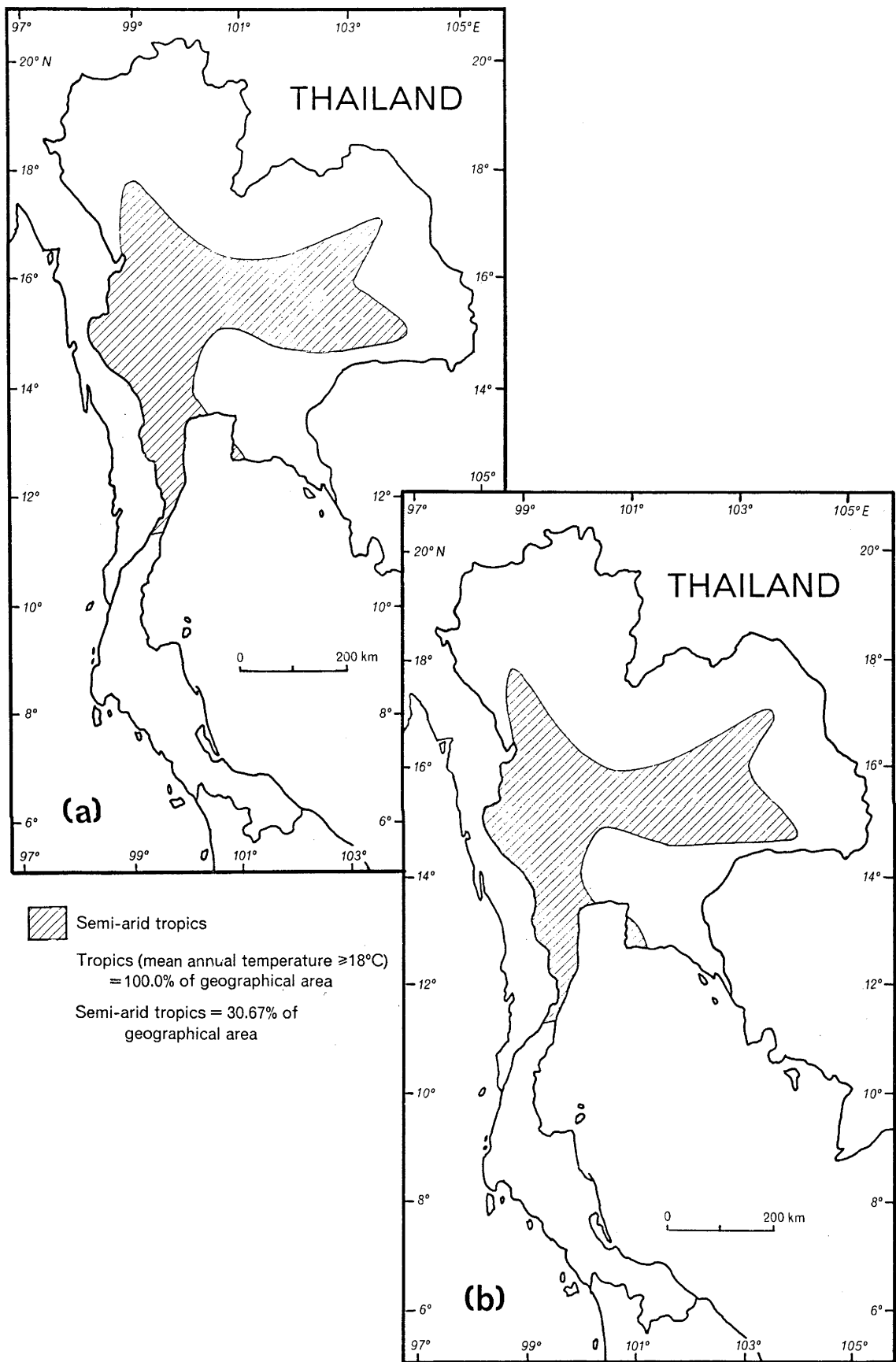


Figure 2-4 : SAT map of Thailand (a) Revised Troll's approach  
(b) Modified Thornthwaite's approach.

### 2.3.2 Hargreaves' approach [Hargreaves, 1971]

Hargreaves (1971) classified Brazil on the basis of monthly moisture availability index ( $MAI = DP/PE$ , where  $DP$  is the dependable rainfall at 75% probability level and  $PE$  is the potential evapotranspiration).  $DP$  is estimated using rainfall data for a large number of years by fitting an incomplete gamma distribution. Hargreaves (1971) defined the semi-arid zone as the region with  $MAI \geq 0.34$  for 3 to 4 consecutive months. This limit is equivalent to  $R/PE \geq 0.50$  [Hargreaves (1975) presented a linear relationship between  $DP$  and  $R$ ]. Boundaries of the SAT zones according to this approach are shown for India, west Africa and NE Brazil in Fig. 2-5. In drawing this map data for 300 locations for each of India and west Africa and 700 locations for NE Brazil are used. In the case of India the  $DP$  values are computed using monthly rainfall data for 1901-1950 (India Meteorological Department [IMD], 1967) and in the case of west Africa these are taken from Virmani et al. (1980) and Reddy & Virmani (1980a); while for NE Brazil these are taken from Hargreaves (1974). It is evident from Fig. 2-5 in the case of India that the high rainfall paddy-rice growing areas of eastern Madhya Pradesh and Orissa are included under the SAT and most of the pearl millet and sorghum growing regions are included in the arid zone. Indeed even larger area than that are seen in Fig. 2-2.

Thus, it seems that the only significant difference between the Troll (1965) and Hargreaves (1971) approaches lies in the time limit chosen for the demarcation of the SAT; Hargreaves (1971) used 3 to 4 consecutive months and Troll as reported by Gray (1970) used 2 to 7 humid months. More arid regions are therefore included within the SAT in the case of Troll (1965) compared to Hargreaves (1971) approach. Even though the Hargreaves approach is as simple as other methods, the computation of dependable precipitation requires long term rainfall records. Also, a computer facility may be needed to fit the data to the incomplete gamma distribution where large data sets are involved. In addition this procedure presents anomalies in dry-land agriculture. Because of these anomalies, this method is also not acceptable for the demarcation of the SAT.

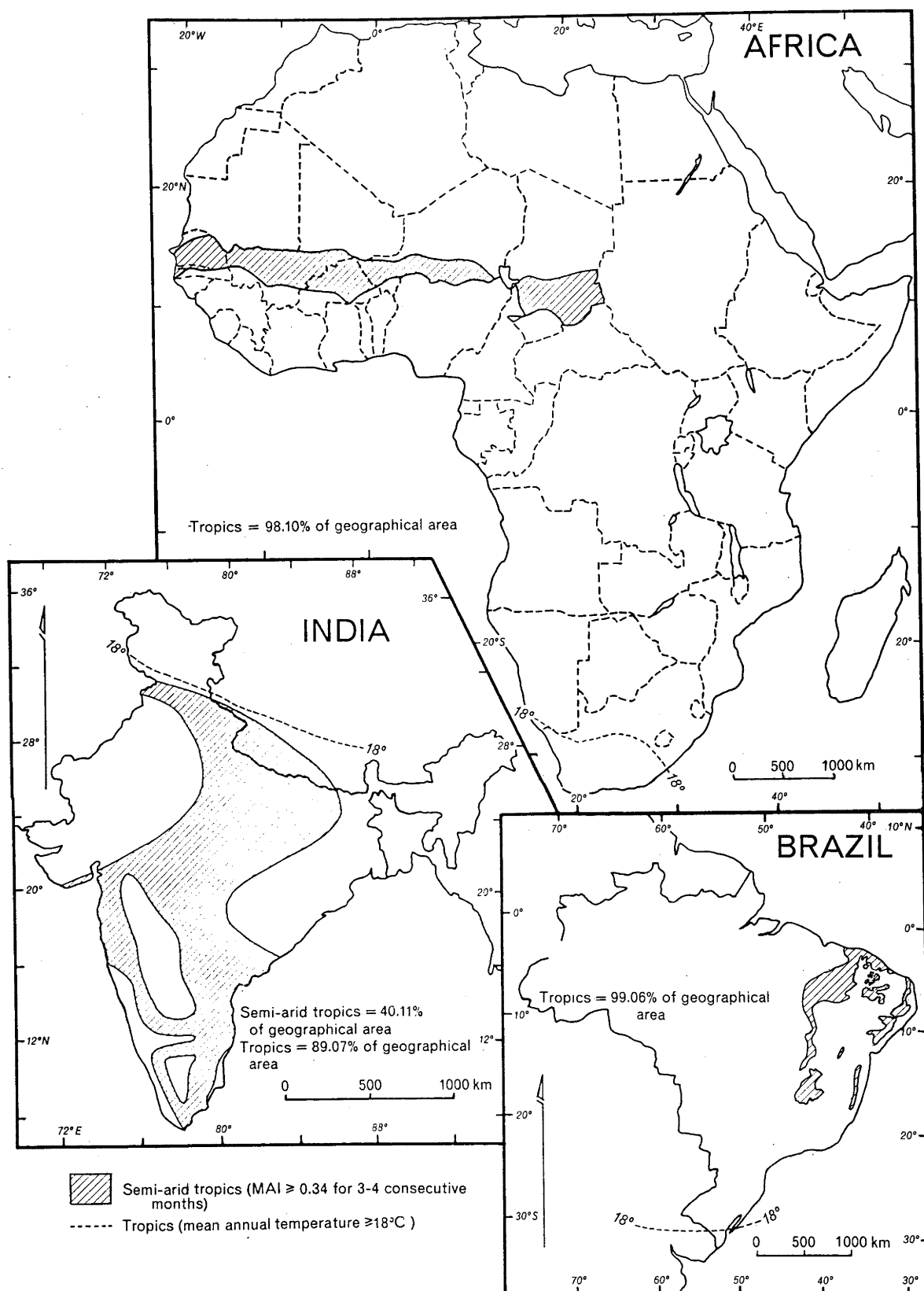


Figure 2-5 : SAT map of Africa, India and Brazil (Hargreaves' approach).

### 2.3.3 Modified Thornthwaite's approach [Reddy & Reddy, 1973]

According to the modified Thornthwaite's approach (Reddy & Reddy, 1973) the semi-arid zone is defined as those regions in which the mean annual rainfall meets the 25% to 75% of mean annual potential evapotranspiration demand (PE).  $[-25\% \leq I_m = ((R-PE)/PE) \times 100 < -75\%]$ . This method is simple and the input data are readily available for a wide network of stations over the world. Using this approach, the SAT boundaries for India are shown in Fig. 2-6. At the upper ( $I_m = -25\%$ ) and lower ( $I_m = -75\%$ ) boundaries of the SAT, the range in mean annual rainfall amount is very low. For example, at the lower limit it is 480-520 mm, at the upper limit it is 1200-1250 mm. In addition, there is a much better correspondence with dry-land crop zone boundaries than was obtained with methods previously described. Important dry-land crops, such as sorghum, pearl millet, groundnut, pigeonpea and chickpea are limited mainly to the defined SAT zone (Fig. 2-3; Easter & Abel, 1973) and it includes the major dry-farming tract of India under the SAT. Also, shown in Fig. 2-6 are the SAT boundaries for Africa, Brazil and Australia. Boundaries for Thailand are presented in Fig. 2-4b. Data sources are shown in Table 2-2.

Because of its simplicity and because it best fits the existing pattern in terms of dry-farming, this method is used to demarcate the SAT as relevant to dry-land agriculture.

The percentage areas that fall within the SAT for individual countries have been ~~estimated~~<sup>modified</sup> for both the Troll (1965) and modified Thornthwaite's approach (Table 2-3). Although some countries have much the same percentage area within the SAT by either method, these do not represent the same geographical regions.

## 2.4 THE ENVIRONMENT OF THE SEMI-ARID TROPICS [SAT]

Before attempting to sub-divide the SAT into agronomically relevant homogeneous zones, it is important to know ~~the~~<sup>SAT</sup> environment in terms of climate, soil and farming systems that influence the dry-land agriculture. This section, therefore, attempts to describe briefly some of these aspects.

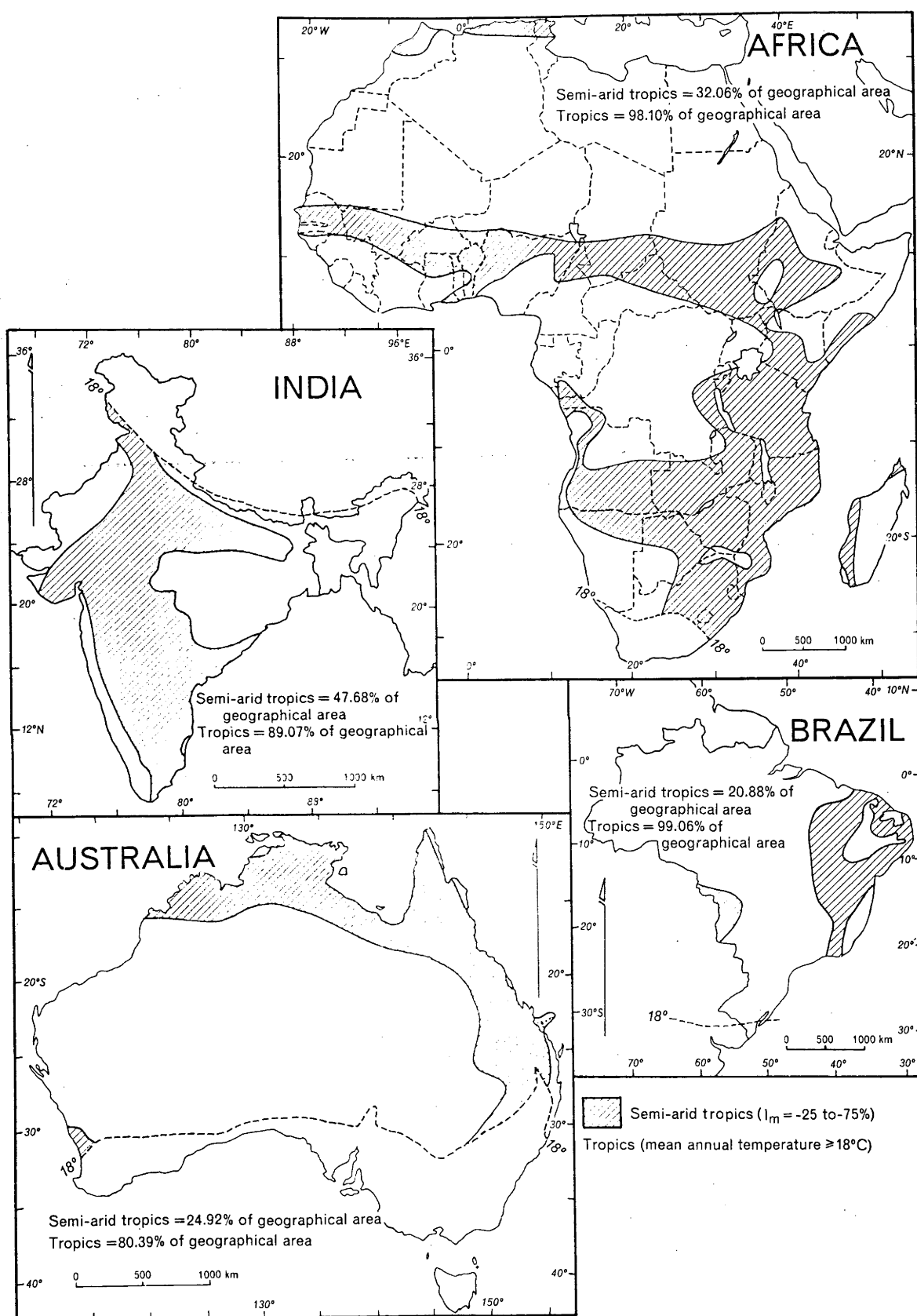


Figure 2-6 : SAT map of Africa, India, Brazil and Australia  
(Modified Thornthwaite's approach).

Table 2-3 : Percentage area under the SAT according to modified Thornthwaite's and Troll's approaches.

Region	Country	Area ( % of geographical area)		
		Tropics*	SAT	
			Method-1	Method-2**
SE Asia	India	89.07	47.68	54
	Thailand	100.00	30.67	60
Oceania	Australia	80.39	24.92	25
Southern & Central America	Brazil	98.76	20.88	12
Africa		98.10	32.06	64.83
	Algeria		5	-
	Angola		64	60
	Botswana		55	100
	Cameroon		17	25
	Central African Republic		34	50
	Chad		27	40
	Dahomey (Benin)		85	80
	Ethiopia (Afars + Issas)		39	50
	Gambia		100	100
	Ghana		43	50
	Guinea		100	70
	Kenya		56	90
	Madagascar		23	50
	Malawi		100	75
	Mali		27	60
	Mauritania		08	25
	Morocco		28	-
	Mozambique		96	50
	Namibia		25	30
	Niger		07	40
	Nigeria		52	75
	Port of Guinea		-	100
	Rhodesia (Zimbabve)		92	100
	Senegal		81	100
	Somalia		21	50
	Sudan		38	60
	Tanzania		100	60
	Togo		50	80
	Tunisia		34	-
	Upper Volta		89	100
	Zaire (Rwanda & Barundi)		11	10
	Zambia		93	100
	Uganda		16	-
	South Africa(Swaziland & Lestho)		46	-

\* Tropics = Mean annual temperature  $\geq 18^{\circ}\text{C}$

\*\* Method-1 : Modified Thornthwaite's approach (Figures 2-6 & 2-4b);  
Method-2 : Troll (1965) approach (Figure 2-1; Values are according to Ryan et al., 1975).



## 2.4.1 Climate

### 2.4.1.1 General

The climate in the tropics is largely controlled by the movement of the Intertropical Convergence Zone (ITCZ), which is the zone of convergence of winds from the high pressure belts of the two hemispheres. The displacement of the ITCZ over the area of influence tends to follow the zenithal position of the sun with a time lag of four to six weeks and hence follows a north-south displacement with summer and winter alternatively. In the area south of Sahel in west Africa, this displacement is an important agroclimatic feature that is directly associated with the rainfall (the greater the distance from the mean position of ITCZ, the shorter the rainy period and the lower the rainfall). In other parts of the semi-arid tropics the rainy periods are associated with ITCZ movement, but the rain causing mechanisms are different particularly in southeast Asia (where tropical depressions/storms and orography play an important role).

### 2.4.1.2 Rainfall

Rainfall in the SAT is summer dominant (April to October in the northern Hemisphere and October to April in the southern Hemisphere) with few exceptions. A few regions, e.g., southern parts of India and eastern parts of Queensland in Australia, also receive rains in winter (Krishnan, 1975). This is also true in several other parts of the world, but is confined to isolated pockets. Some typical rainfall patterns in the SAT are shown in Fig. 2-7. Indore (India), Tambacounde (Senegal), Niamey (Niger), Asmara (Ethiopia), Pretoria (South Africa), Campos Sales and Aracati (NE Brazil) present a single peak (unimodal distribution); Ahmednagar (India) has a double peak while Voi (Kenya) has two separate rainfall pulses (bimodal distribution). Madurai (India) has a unimodal pattern under winter rainfall and Anantapur (India) and Inhambane (Mozambique) have long rainfall season influenced by both summer and winter rainfall. The rainfall at any given location has both long-term and short-term variations. Long-term rainfall trends and fluctuations differ significantly over different continents and also over different regions within the same continent (Parthasarathy & Dhar, 1974, 1978; Tyson, 1978; Reddy, 1984). Figure 2-8 presents one such example of the climatic fluctuations in south Africa (Mahalapye in Botswana; Reddy & Singh, 1981). Seasonal and annual rainfall totals

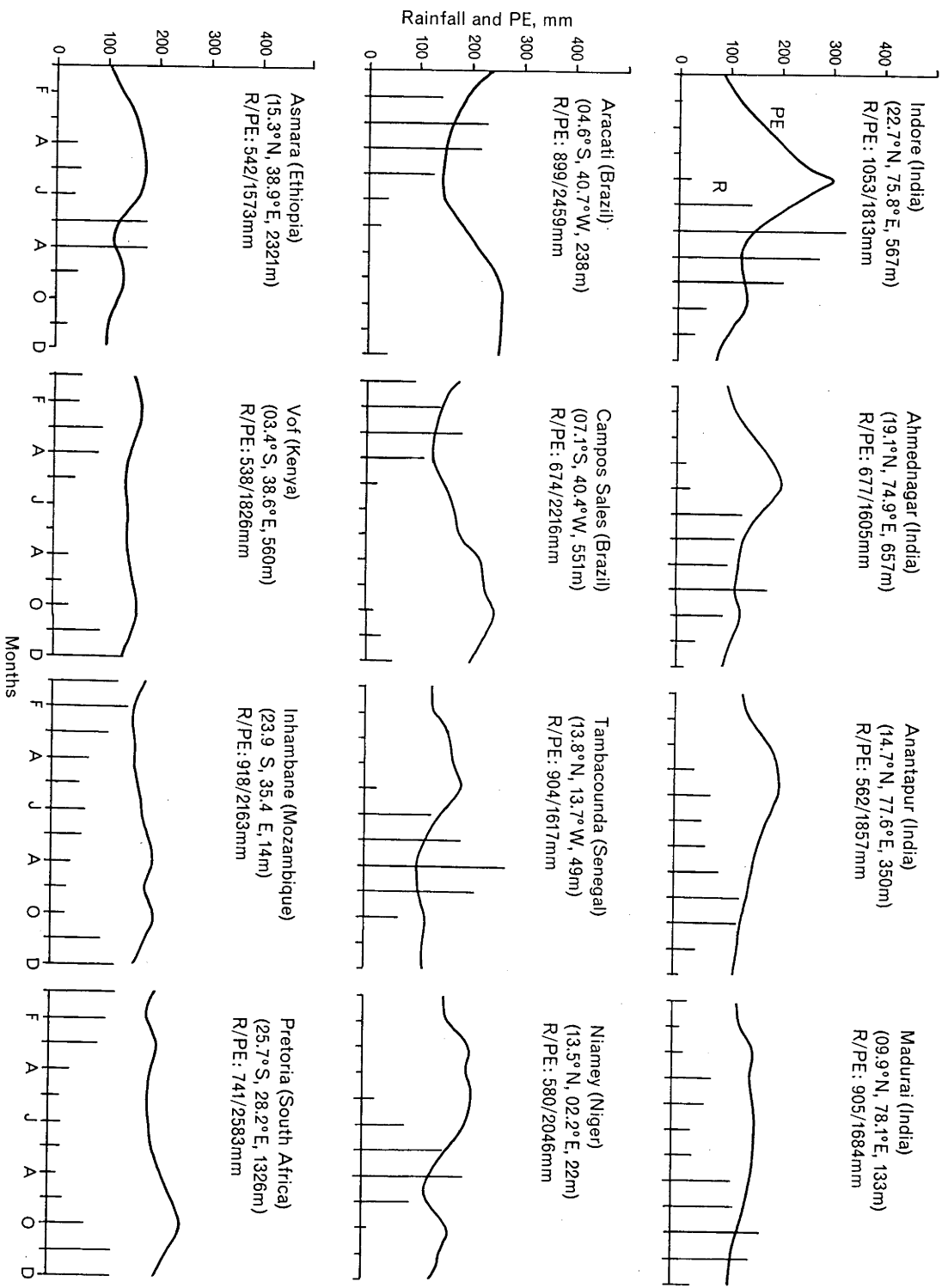


Figure 2-7 : Seasonal distribution of rainfall and PE for 12 selected locations in the SAT.

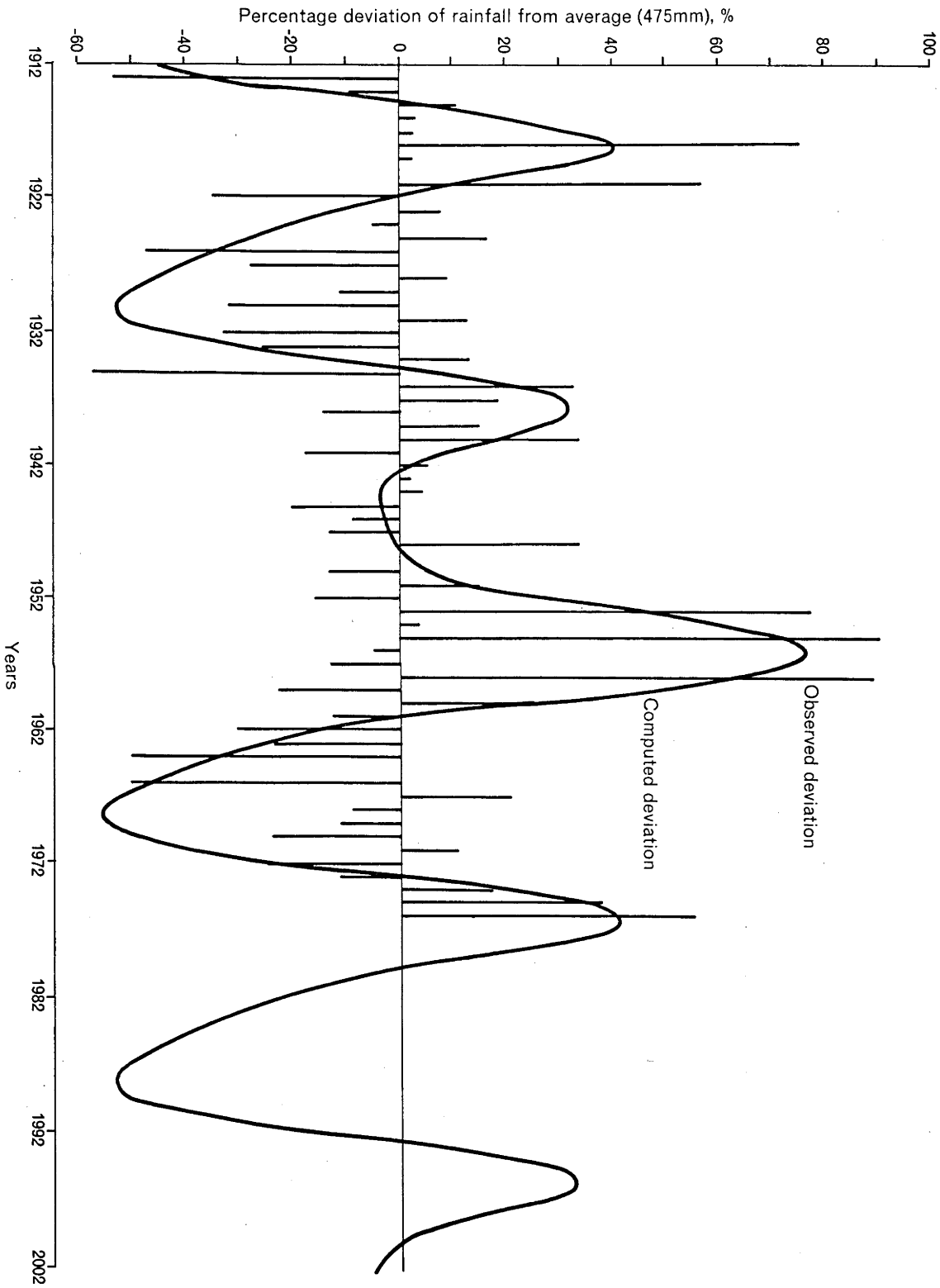


Figure 2-8 : Observed and estimated seasonal trend in mean annual rainfall (Mahalapye, Botswana).

follow the normal distribution (Rao et al., 1972a; Griffiths, 1967). The square root of monthly rainfall also shows normality (Griffiths, 1967). In general the SAT is characterized by a short rainy season, an erratic rainfall distribution, frequent droughts and high intensity storms of varying duration, wide variations in rainfall amounts over regions and seasons and wide variations in arrival and withdrawal of rains (Reddy, 1975).

#### 2.4.1.3 Radiation, temperature and relative humidity

Direct measurement of global solar radiation is restricted to a limited network of stations, but the application of empirical relationships based upon sunshine hours or cloud etc. has permitted calculation of solar radiation for a much wider network of stations (Reddy, 1971a,b; Reddy & Rao, 1973; Reddy, 1973, 1981c; Reddy et al., 1984b). Solar Radiation is a conservative element that shows only moderate year-to-year variation. Annual global solar radiation can vary between 400 to 550 cal/cm<sup>2</sup>/day (or 0.042 MJ/m<sup>2</sup>/day) (Landsberg et al., 1963; Thompson, 1965; Reddy & Rao, 1976; Reddy & Virmani, 1980b; Reddy et al., 1984b). However, on a daily basis this may vary from as low as 100 cal/cm<sup>2</sup>/day on an overcast day to as high as 750 cal/cm<sup>2</sup>/day on a clear day. <sup>spatial</sup> Variation in <sup>average annual</sup> temperature among the SAT countries is low compared to other climatic regimes (Krishnan, 1975). The west African SAT show (Table 2-4) little variation even over seasons. Variation in temperature with season and latitude is systematic (Reddy & Virmani, 1980b). Relative humidity is high in Asian SAT (Table 2-4) and northeastern parts of Australia compared to other SAT regions.

#### 2.4.1.4 Potential evapotranspiration

The potential evapotranspiration (PE) is generally high (> 1800 mm) in most parts of the SAT except Asian SAT. The high PE values particularly in the post-rainy season in Africa (Reddy & Virmani, 1980b; FAO-M. Frere, pers. comm.) and NE Brazil (Reddy, 1981a) limit double cropping or rainy season fallowed, post-rainy season cropping compared to Asia (Rao et al., 1971; Reddy, 1981b). Figure 2-7 presents the PE patterns over a few selected locations in the SAT.

Agriculture in the SAT is a gamble on rainfall. Water surpluses and deficits and their duration are of great importance in evaluating water and land management systems for better crop production. While it is important to consider the water receipts over a given area, in considering effective

Table 2-4 : Seasonal variation of temperature and relative humidity  
in world SAT.

SAT Region	Element*	Seasons**			
		Winter (Dec-Feb)	Summer (Mar-May)	Monsoon (Rainy) (Jun-Sep)	Postmonsoon (Postrainy) (Oct-Nov)
North Africa	T	25.3	29.4	26.7	26.9
	RH	40	48	76	63
South Africa **	T	20.1	24.7	24.5	23.1
	RH	58	59	77	67
Australia **	T	20.8	27.8	29.5	25.2
	RH	43	45	60	39
India-9 to 15°N	T	25.6	30.2	28.6	26.5
	RH	63	57	65	72
-15 to 25°N	T	22.4	30.4	27.9	25.2
	RH	48	41	72	56

(Source: Krishnan, 1975).

T = Average temperature, °C;

RH = Average relative humidity, %

\*\* = For Southern Hemisphere areas the seasons are reversed (on months to that effect).

water use. one is also concerned with the loss of water. Hence, in agroclimatic studies, the predominant meteorological factors to be considered are precipitation and potential evapotranspiration as they respectively represent the water supply and potential water need. The average distribution of rainfall when studied along with the variations about the average, both in frequency and extent with respect to PE, gives better insight into its agronomic importance in different regions.

#### 2.4.2 Soils

As with climate, wide variations are seen in soil types both at micro- and macro-scale. The diversity of the SAT soils is illustrated by a map of Aubert & Tavernier (1972). This shows four major soil types:

1. alfisols (which constitutes the major part of the SAT soils);
2. vertisols;
3. entisols;
4. aridisols (for the sake of clarity, the US Soil Taxonomy system of classification is used).

The details on the SAT soils according to Troll's approach were presented by Kampen & Burford (1979) and according to the revised Troll's approach (Reddy, 1977a) by Swindale (1982). Sanchez (1976) presented some general characteristics of these soils.

##### 2.4.2.1 Soil types

Alfisols [red and gray soils]: These soils are fairly shallow ( < 100 cm) and are moderately well drained. The agricultural value of these soils is usually rated poor to average. Structural stability is generally poor and results in surface compaction and crusting. This increases soil and water losses in runoff and makes erosion hazards high.

Vertisols [black soils]: These are dark cracking, clay soils of low permeability and poor internal drainage. The clay fraction contains a high portion of 2:1 lattice clays which swell on wetting and shrink on drying. Commonly, these soils are deficient in nitrogen, phosphorous and sometimes zinc but are occasionally very fertile. The poor internal drainage creates excess water problems.

Entisols [Alluvial soils]: As the name implies they are found in present or former river valleys and are recent deposits that have been

little affected by soil-forming processes. Because these soils have not undergone the adverse action of tropical weathering and leaching they can be among the most productive soils in the world.

Aridisols [sandy soils]: Aridisols are found primarily along the border regions of arid and semi-arid zones. They are very sandy soils, hold little water, are easily workable, but are subject to wind erosion.

The above paragraphs provide an indication only of the diversity of the major SAT soils. Some important characteristics influencing crop growth can be identified as: soil depth, soil moisture storage capacity, soil erosion, soil fertility, and crusting and drainage. These are discussed below briefly.

#### 2.4.2.2 Soil characteristics

Soil depth: Soils vary a great deal in depth from a few centimeters, ( < 50 cm) to several meters, ( > 2 m) thus affecting the rooting depth as well as water holding capacity. Compact zones like the lateritic plinths in Africa and Latin America may also impede water and root penetration.

Soil moisture storage capacity: The available water storage capacity within the profile is the crucial factor for crop survival and production. Soils show great variability in ability to store water – ranging from coarse sandy soils having limited water holding capacity (even less than 50 mm) to heavy clayey soils having appreciable water holding capacity (even more than 250 mm).

Soil erosion: Kinetic energy associated with high rainfall intensity is the prime cause of serious erosion (Greenland, 1977). In Africa and Latin America where bush fallow or swidden agriculture is practiced, a major erosion threat is posed by increasing fallow periods and thus decreased protection of the soil surface.

Soil fertility: Most SAT soils have low fertility (Jones & Wild, 1975; Sanchez, 1976). The mode of formation of most soils in the SAT environment has resulted in their being well endowed with bases but they are deficient in nitrogen and phosphorous. Sulphur deficiency is common in Africa. Marginal zinc deficiency also appears to be common.

Crusting and drainage: Soil crusts usually are formed as a result of compaction at the immediate surface due to an externally applied force such as heavy rain. This reduces infiltration, and restriction of seeding emergence also takes place. If water originating from the surface does not drain away sufficiently fast, water-logging occurs and anaerobic conditions

prevail. Under these conditions the soil is too wet for normal cultivations to take place. It is possible to improve surface drainage by improving soil structure.

### 2.4.3 Farming systems

#### 2.4.3.1 Cultivation systems

Cultivation systems in the SAT are multitudinous but three main forms may be recognized (Nye & Greenland, 1960; Morgan & Pugh, 1969; Ruthenberg, 1971, 1974). They are:

1. **Shifting cultivation** - a more or less haphazard movement of cultivation from place to place as fertility is exhausted or weeds become uncontrollable;
2. **Rotation bush fallowing** - a deliberate alternation between cropping and bush regeneration. The duration of each cycle depends on soil fertility, weeds and population pressure;
3. **Continuous cultivation** - associated with high population density, especially in the vicinity of large towns.

The first two systems are prevalent in Latin American and African SAT while the latter is seen in the Asian SAT. As increasing populations create a demand for food, agricultural systems are shifting more towards the third system mostly using artificial fertilizers.

#### 2.4.3.2 Crops and cropping systems

Several forms of cropping are practiced in the SAT. These include single cropping, intercropping and double cropping. Intercropping is the practice of growing 2 or more crops together on the same piece of land, the crops being planted at the same time in various geometric patterns but harvested at the same time or different times. Where seed of mixed crops is simply broadcast with no geometric pattern, this is termed mixed cropping. Relay cropping refers to the practice of planting a second crop 2-4 weeks before harvest of the standing crop. In double or sequential cropping the second crop is planted after the harvest of the first crop (Rao & Natarajan, 1981).

Subsistence food crops are millet, sorghum and groundnut in the drier zones and maize, cassava and various legumes in the wetter. Intercropping is common and many crop combinations are used (Norman, 1975; Patrick, 1972; Rao & Natarajan, 1981). About 44% of the world's



sorghum, 55% of the pearl millet, 90% of chickpea, 96% of the pigeonpea, and 67% of the groundnut are produced and consumed in the SAT. These crops are the main source of energy, protein and fat for people living in the SAT (Kanwar, 1979).

Agricultural systems in the African SAT differ markedly from those of India, not so much due to the crops involved but, because of differences in soils, different rainfall patterns and socio-economic conditions. There is little use of animal power and most of the operations are performed by hand, using hoe and cutlass. Crop yields are low, cereals average 500-600 kg/ha; legumes such as cowpea and soybean produce 250-300 kg/ha; and groundnut yields about 700 kg/ha. In west Africa crops are grown entirely rainfed and the major crops, sorghum, millet, groundnut, cowpea and cotton occupy about 60-80% of the cultivated land. Others, such as root crops, vegetables, maize, tobacco, sugarcane and paddy-rice, cover about 15% of the cultivated area (Kassam, 1976). In Nigeria, sorghum/millet, cotton/cowpea are the most common 2-crop mixtures. Other mixtures are sorghum/groundnut, pearl millet/sorghum/groundnut, cotton/sweet potato/cowpea and pearl millet/sorghum/cowpea/groundnut (Norman, 1975). In Upper Volta pearl millet is prominent in the northern zone; sorghum and pearl millet in the central zone; sorghum and maize in the southern zone. With respect to soil types, pearl millet is found on relatively shallow soils, sorghum and maize on deep sandy loam and paddy-rice on soils having high water capacity (Stoop & Pattanayak, 1979). In Senegal, groundnut and pearl millet are grown in the north and central zones and, to a lesser extent, sorghum and cowpea; cotton, maize and paddy-rice are grown in central eastern parts; and groundnut, maize/cowpea; sorghum/maize in the southern parts (Charreau, 1974). In NE Brazil double cropping is not practiced because of the short rainy season with high PE rates and low moisture retention capacity of the soils. The most important cropping system is intercropping. In areas where the rainfall is too erratic and soils too poor for normal agriculture with food crops, perennial cotton is grown either single or intercropped with cactus, or, in better soils, intercropped with food crops such as maize, maize/cowpea, maize/beans (Lima & Quiroz, 1981). Mafra, et al. (1979) indicated that maize can be replaced by sorghum in maize/legume systems without damage to the legume yields, because sorghum is less affected by drought than maize.

At present, most of northern Australia is used for extensive cattle grazing. Lack of infra-structure, markets and suitable mechanized technologies for commercial cropping has hindered development. Nix (1978) estimates that only 3 million hectares might ultimately be cropped because of terrain and soil constraints. Perhaps ten times this area might be suited to improved pasture development (Nix, 1978).

In India, farmers traditionally leave the deep black soils fallow during the rainy season and crop only during the post-rainy season using the residual soil moisture (International Crops Research Institute for the Semi-arid Tropics (ICRISAT), 1981). The farmer has long recognized that trying rainy season cropping is less assured than growing a post-rainy season crop on soil moisture conserved in the profile. But, this is not advisable on shallow vertisols and alfisols as insufficient water can be retained in the soil to grow a post-rainy season crop.

#### 2.4.4 Land and water management

Where rainfall is at least moderately high and is dependable, the montmorillonitic clay of deep and medium deep vertisols makes them very difficult to manage. Thus, they are very hard when dry and extremely sticky when wet, and can be cultivated easily only within a limited range of moisture conditions. Once the rains have started, the soil rapidly becomes too sticky for cultivation and sowing. If the rains are heavy, crop water-logging may occur, and opportunity for timely weed control is restricted. To overcome such problems and to increase food crop production in the SAT, ICRISAT has suggested new farming practices based on experimental findings both by ICRISAT and ICAR scientists. Examples are:

- Improved field drainage (ridge and furrow system);
- dry sowing ahead of the monsoon (some farmers do follow this practice traditionally in India);
- Post-harvest cultivation;
- Pre-harvest cultivation;
- use of hybrid seeds, fertilizers;
- using improved seed and fertilizer drills to ensure proper placement and stand;

- **appropriate** plant protection:
- **timely** harvest:
- **storing** runoff for supplemental irrigation (Krantz, 1979; Indian Council of Agricultural Research (ICAR), 1982).

The idea of runoff collection and use for supplemental irrigation presupposes that the potentials for using the available root profile storage more efficiently to buffer discontinuities in rainfall have been fully utilized. On any given soil type, the potential for supplementary irrigation from stored runoff is influenced strongly by the rainfall patterns, terrain and by subsoil conditions. The actual feasibility of this technique will, therefore, always be location-specific.

Benefits from supplemental irrigation from stored water are more likely on alfisols than on deep to medium-deep vertisols because alfisols have higher runoff potential and they have a lower water-storage capacity. For more details on the above observations reference can be made to Krantz & Russell (1971), Kampen, et al. (1975), Kampen (1976).

#### 2.4.5 Discussion

Although high temperatures and radiation encourage rapid crop growth, production is limited by insufficient water, for everywhere in the SAT the annual PE exceeds rainfall. Many soils are sandy and low in crop nutrients. Because of their sandy texture many top soils have poor moisture holding capacity. The effect of this deficiency on crop growth may be aggravated by restricted rooting depth, due to a shallowness of profile or a compact clay horizon. Soil structure is generally weak. Any structure that exists in the top-soil under natural vegetation rapidly deteriorates under cultivation. During humid periods sub-soil horizons of low permeability may cause surface water-logging. In many years runoff and soil erosion are almost inevitable during the heaviest storms. Runoff and erosion involve the loss of soil and soil nutrients. The farmer suffers many problems which his counterpart in temperate climates does not: rain varies unpredictably both between and within years, the soil quickly loses its productivity in tropical storms, while insects, disease and weeds which thrive in high temperatures cause heavy crop losses. Nearly 95% of farmers manage less than 2 hectares of land and farming is primitive, with only human and bullock power and simple tools available. In many

respects the agricultural environment in the SAT is a harsh one. Traditional cropping systems reflect climatic variability and traditional practices as well as economic trends and availability of markets. Disease-resistant varieties are largely unavailable to small-scale farmers, and fertilizers are expensive. The most common system is intercropping: by mixing crops the farmer can have a longer cropping season, and longer protection for the soil from the sun. He can also grow a great variety of crops and can achieve greater yields per unit area.

## 2.5 SUMMARY

There is a great diversity in the usage and practical application of the term "semi-arid". Two probable reasons for such diversity are: first, some workers have defined the SAT relative to "natural vegetation" boundaries and others have defined the SAT in relation to cultural or land use boundaries. Secondly, climatic indices differ both in terms of their choice of variables and/or choice of class intervals. Most approaches use two climatic elements: (1) rainfall that supplies water for plant growth and (2) evaporative demand, that expresses moisture need for optimum plant growth. But the parameters used to represent these two climatic elements are significantly different. Older methods used temperature as a surrogate for evaporative demand and defined the SAT relative to natural vegetation boundaries while others used estimated potential evapotranspiration or class A pan evaporation and defined the SAT relative to vegetation types or food crops. Two broad modes of defining the semi-arid zones in terms of moisture and evaporative demand are identified. These are annual indices and the duration of moist and/or dry periods. Three methods were compared and analysed in order to understand their potential applicability for the demarcation of the SAT with reference to India, Africa, Brazil, Australia and Thailand. These were Troll's (1965) humid period as modified by Gray (1970) and Reddy (1977a); Hargreaves' (1971) dependable moist period; and the modified (Reddy & Reddy, 1973) Thornthwaite's annual moisture index. The term semi-arid is defined here as the zone of dry-land agriculture bounded on one side by areas where rainfed crop production is uneconomical (arid zone) and on the other by the sub-humid zone, where rainfed dry-land crop production is risky. The modified Thornthwaite approach provided the most relevant agriculturally-oriented demarcation of the SAT. The model is not only simple but uses

input data that are available for a global network of stations. The other two methods present anomalies concerning the distribution of food crops.

In order to define the tropics the limit proposed by Koppen (1936) was used. The semi-arid tropics are thus defined as regions with mean annual temperature  $\geq 18^{\circ}\text{C}$  and the mean annual rainfall meets 25 to 75% of the mean annual potential evapotranspiration. The SAT includes major dry-land agricultural zones in the tropics with mean annual rainfall varying between 500 and 1250 mm. The upper and lower limits of rainfall show slight variation over different countries following the potential evapotranspiration level. Major dry-land crops are pearl millet, sorghum, pigeonpea, and groundnut. The SAT present wide variations of climate, soils and farming systems. Building appropriate relationships between these factors involves agroclimatic classification, the sub-division of the SAT into agronomically relevant homogeneous zones. This work is dealt in the chapters which follow.

## CHAPTER 3

### AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID

#### TROPICS: 1. A METHOD FOR THE COMPUTATION OF CLASSIFICATORY VARIABLES

### 3.1 INTRODUCTION

In this study, the purposes of classification are to assist in understanding climatic limitations to dry-land agriculture in the SAT, to provide guidance in the transfer of technology and to assist in the development of improved farming practices through better utilization of natural resources.

According to Arkely (1976), to be both comprehensive and effective, the differentiating characteristics used to form classes should contain the maximum possible information; the choice of variables to be included in the classification should be such that the number of variables are large and the general kinds of variables included are well represented. The inclusion of large numbers of logically related characters should be avoided as they tend to create an inadvertent extra weight to such a group of characters in the classification.

Two types of attributes (or variables) can be envisaged, namely, general or basic (commonly used) and derived (not so commonly used). Basic variables commonly used are of two types:

1. *statistical* parameters, such as mean annual rainfall, mean monthly temperature and the coefficient of variation (c.v.) of rainfall;
2. *probabilities*, such as the probability of obtaining specific amounts of rainfall during specified periods [or fixed amount probabilities] (Robertson, 1976), the rainfall expected at certain probability levels [or fixed probabilities] estimated by using incomplete gamma analysis (Hargreaves, 1971).

Both types of basic attributes are generally derived by standard statistical procedures.

Derived attributes are developed from concepts which vary according to the purpose of the study. These can be divided into three classes:

1. *simple* ratios such as the ratios of rainfall to potential evapotranspiration or dependable rainfall to potential evapotranspiration (Hargreaves, 1971);
2. *probabilistic* parameters such as the probabilities of derived variables like mean growing season, wet and dry spells during the growing season;
3. *functionally* derived parameters like dissimilarity variables presented in Chapter 4.

If the different derived parameters or basic variables are interrelated, their relationship is first established. Then, using this established function a new variable can be derived. This new variable demonstrates the particular characteristic behaviour of that environment relative to others.

Even though the SAT map (Fig. 2-6), as demarcated using a modification of Thornthwaite's approach, presents uniformity in dry-land or rainfed agricultural zones, on a broad scale there are significant internal variations in terms of their production potential (ICAR, 1982). The National Bureau of Soil Survey and Land Use Planning has divided India into agroecological regions based on climatic and ecological conditions (Murthy & Pandey, 1978). The SAT are subdivided into four regions (Fig. 3-1a) and the third subdivision was further divided into two parts (Reddy & Virmani, 1980b), namely (IIIa) undependable rainfall and (IIIb) dependable rainfall. Within all these subdivisions the rainfall amount varies significantly, from 600 to 1000 mm, and the length of the growing season varies between 90 and 180 days (Fig. 3-1a). The growing season data have been based on the agroecological zones of FAO (M. Frere, pers. comm., 1980) in which there are wide variations in soils (Fig. 3-1b) and crops (ICAR, 1982).

Farmers in the SAT are not only interested in the period of available moisture but also the time it commences. In heavy clay soils (e.g., vertisols), primary tillage and seeding is difficult once the soil is wet. The time of commencement of sowing rains is also important for the proper planning of seeding operations. The methods of Troll (1965) and Cocheme & Franquin (1967) rely on normal climatic data and, therefore, do not take into account the variability of the weather from year-to-year. Accounting of variability in weather is essential for identifying the proper crop and cropping pattern which is most productive with least risk. Even though the Hargreaves (1971, 1975) method is based on rainfall at the

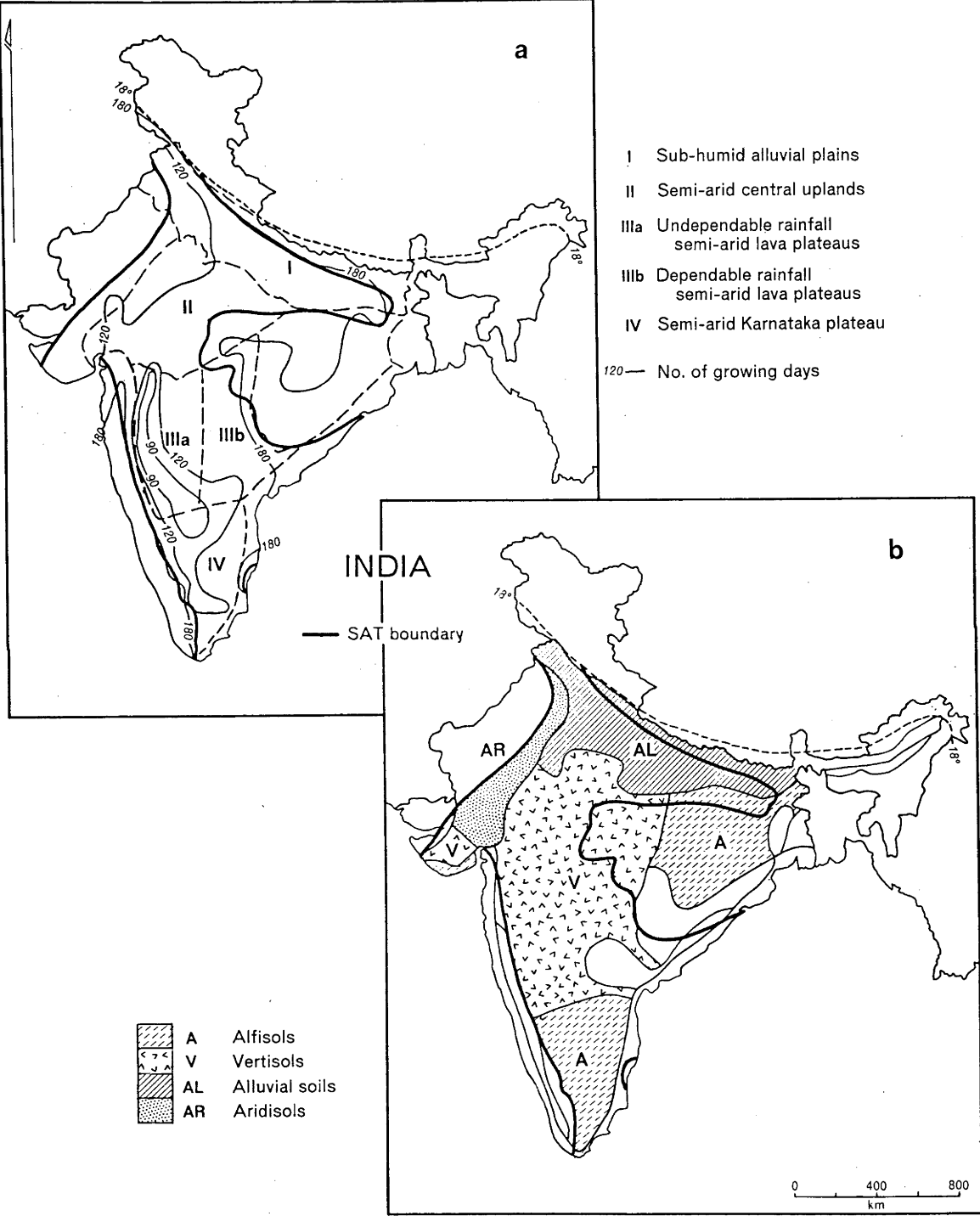


Figure 3-1 : (a) Agricultural subdivisions and length of growing season  
(b) Predominant soil types.



75% probability level, his estimates do not represent consecutive periods of the same year. Consideration of consecutive periods are important in understanding the probabilities of crop failure or near failure. Estimating the production potential of various regions, and the associated risk versus input levels, depends on knowledge of such probabilities.

Recently, several scientists (Nix, 1975; Russell & Moore, 1976; Russell, 1978; Austin & Nix, 1978; Gadgil & Joshi, 1981; Reddy & Virmani, 1982) have used numerical techniques for grouping locations according to agriculture. However, in the majority of these studies the data sets were the averages of annual, monthly or weekly climatic data only. Some of these studies show anomalous groupings when compared with the observed agricultural production patterns and with standard climatic classifications: examples are Koppen (1936), Thornthwaite (1948), Papadakis (1975). Such anomalies are due more to the variables used than the classification procedure adopted.

Clearly, variables estimated from average monthly, seasonal and annual rainfall based on long-term weather records have limited practical applicability in agricultural production studies. They can give a broad outline of productivity gradients but not of associated risks. While methods used to define the length and beginning of the moist period were found to be of limited practical applicability using long-term average data, the basic concepts are very valuable aids for further development in this direction.

In the present study, a modified method after Cocheme & Franquin (1967) and Hargreaves (1971, 1975) is presented for estimating agroclimatic variables that are to be used to classify the climate of the SAT into the relevant agronomically homogeneous zones. A comparison is made between the results of the present approach and those of Troll (1965) as revised by Reddy (1977a), Hargreaves (1971), Cocheme & Franquin (1967).

### 3.2 METHODOLOGY

The meteorological data used and the sequence of steps followed to develop a method to derive classificatory agroclimatic variables for the relevant agronomically homogeneous zones of SAT are presented in the following few pages and in Fig. 3-2.

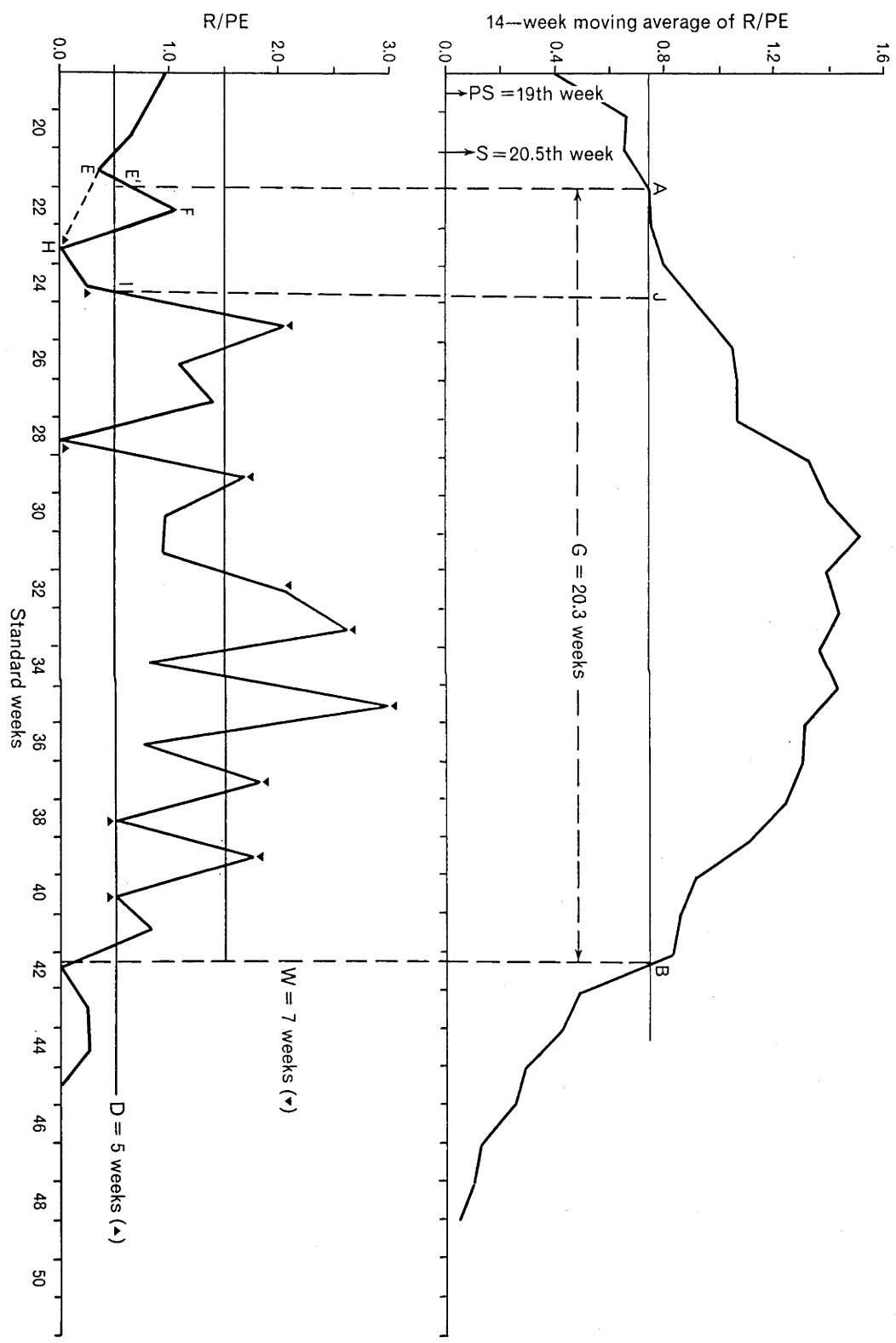


Figure 3-2 : Computation of PS, S, G, W, and D (hypothetical case for one year).

### 3.2.1 Input data

The basic data consist of observed weekly rainfall (R) and estimated potential evapotranspiration (PE). The details on the computation of PE values for individual years were presented by Reddy (1979a) and are given in brief in Appendix E.

### 3.2.2 Estimation of variables

(1) Estimate R/PE for standard weeks 1-52 [for details see Appendix C] for N years, where N represents the number of years for which the weekly rainfall (R) data are available (N should be more than 15 years and preferably more than 25 years to obtain meaningful statistical parameters).

#### Available effective rainy period [G]:

(2) For each week of the individual years, compute a 14-week moving average of R/PE centred around a particular week. In these computations, if  $R/PE > 3.0$  for any week then R/PE is set at 3.0 [under the SAT this limit is considered as the average effective water limit on an average soil type]. The 14-week moving average for weeks 20-21 is an average of the values for weeks 14-27, and the 14-week moving average for week 21-22 is an average of the values for weeks 15-28, and so on. This procedure generates smoothed estimates of R/PE on a continuous basis for the consideration of past and future moisture conditions. Short duration crops, like pearl millet and sorghum in the SAT, require about 90-100 days from seeding to maturity. The 14-week (98-day) moving average is chosen to reflect this duration. At least 7-8 weeks of optimum moisture are required for a high yield.

(3) Determine the 'available effective rainy period (G)' as the consecutive period in the year which simultaneously fulfills the conditions:

- All weeks within period G have a 14-week moving average of  $R/PE \geq 0.75$ ;
- The week at the beginning of the period has a value of  $R/PE \geq 0.50$  (a value of  $R/PE \geq 0.75$  is chosen because this is in the optimum range for plant growth).

This method is illustrated in Fig. 3-2 by taking a hypothetical case for one year. The upper part of the figure represents a 14-week moving average from A to B with  $R/PE \geq 0.75$ . This excludes the period in which water is available to crops through soil water storage, which will be longer

in the case of vertisols and shorter in the case of alfisols. The bottom curve in Fig. 3-2 represents the pattern of  $R/PE$ . The starting point, A, of the 14-week moving average with  $R/PE \geq 0.75$  lies between E and F, i.e., at E' (where  $R/PE \geq 0.50$ ), and G is represented by A-B (20.3 weeks). If the  $R/PE$  curve follows the dotted line, to reach H from E, then  $R/PE$  would not be  $\geq 0.50$  until I (after A), and in this case G is represented by J-B (17.4 weeks), which is less than A-B.

**Week of commencement time of sowing rains (S):**

(4) The week before the beginning of the available effective rainy period is taken as the 'week of commencement time of sowing rains (S)'. S is week 20.5 for A and week 23.4 for J in Fig. 3-2. In this definition, the commencement time of sowing rains naturally differs from the onset of 'normal' rains, as the former requires a threshold limit of rainfall to be satisfied. Generally, this threshold is the amount needed to bring the top few centimetres of soil up to the moisture content required to germinate seed in that environment. It is specified here as  $R/PE \geq 0.50$ , with a continuous moist period following.

(5) Pre-sowing cultivation and seed-bed preparation (PS) are started when the 14-week moving average curve of  $R/PE$  crosses the 0.50 limit and when the particular week has  $R/PE \geq 0.25$ . In Fig. 3-2, PS is represented by week 19.

**Wet and dry spells within G period [W and D]:**

(6) Compute the number of weeks in the available effective rainy period for which  $R/PE \geq 1.5$  and  $\leq 0.50$ , which are termed wet (W) and dry (D) spells, respectively. In Fig. 3-2, if we consider G as A-B, then  $W = 7$  weeks and  $D = 5$  weeks; or if we consider G as J-B, then  $W = 7$  and  $D = 3$  weeks only.

Hargreaves (1974) stated that during the rainy season, in months when the moisture availability index (MAI) exceeded 1.34, in the semi-arid regions of northeast Brazil, the moisture in the root zone was excessive and likely to hamper plant growth. The soils there are shallow, stony and have a low level of organic matter and clay content. The SAT areas in India are primarily located on soils with a much higher water-holding capacity, particularly vertisols and Indo-Gangetic alluvium (Fig. 3-1b, Reddy & Virmani, 1980b). It has been observed at the ICRISAT Centre that in the deep vertisols, short-term water-logging is quite common in the months of July, August and September. A significant detrimental effect

of excessive water in the root zone is observed in September, when the soil profile is almost filled to capacity by the July and August rainfall. Based on this, Reddy & Virmani (1980b) suggested that locations with two successive months with MAI of 0.66 or more present a water-logging hazard. However, the above two limits can be approximated by R/PE of 2.0 and 1.0, respectively [Hargreaves (1975) observed that the dependable rainfall at 75% is linearly related to average monthly rainfall]. As a compromise between these two extremes, an intermediate value was chosen, i.e., R/PE of 1.5 or more, which is approximately equal to an MAI of 1.0.

Average maize yields in the USA are obtained in several midwestern states, where actual evapotranspiration rates average 72% of the potential rate. Crop failure is common when the actual evapotranspiration rates fall below 50% of the potential rate (Eagleman, 1976). This fact is also evident from the yield prediction equations of Jensen (1968), Hiler & Clark (1971) and Minhas et al. (1974), as derived by Reddy (1983b), and from the results of Hiler et al. (1974).

#### Method of computing averages for S, G, W and D:

Repeat steps 3 to 6 for N years. Assuming that for some (x) years, condition 3 is not satisfied, one of two possible ways can be used to calculate the means and standard deviations (s.d.) for G, S, PS, W and D.

(i) For those years in which condition 3 is not satisfied, assume that each of the five above mentioned variables equal zero; then calculate the mean and s.d. for each of the 5 variables for N years. The mean and s.d. values for S, PS, W and D estimated using this assumption are misleading, with the means representing underestimates.

(ii) Considering years N-x, for which condition 3 is satisfied, compute the mean and s.d. values of S, PS, W and D for these years. The mean and s.d. estimated this way represent overestimates for G. However, possible wet and dry spells within the available effective rainy period, if they exist, are defined and this is in fact what an agronomist is interested in.

It appears, therefore, that the first procedure is most suitable for estimating G, while the second procedure is the best for the remaining 4 variables. Means and s.d.'s for these five variables are denoted by G, S,

PS,  $\bar{W}$  and  $\bar{D}$ <sup>1</sup>, and  $\sigma$ ,  $\delta$ ,  $\gamma$ ,  $\alpha$  and  $\beta$ , respectively. There is some ambiguity in the terms  $\bar{W}$  and  $\bar{D}$  in relation to  $\bar{G}$ . That is, at lower values of  $\bar{G}$  it is possible that  $\bar{W} + \bar{D} > \bar{G}$ , even though for individual years  $W + D$  is always  $< G$ . The error involved, however, is less than one week (overestimate) for both  $\bar{W}$  and  $\bar{D}$  which is generally smaller than the s.d. [ $\alpha$ ,  $\beta$ ]. There is unfortunately, no other way to overcome this problem. Consequently, the procedure of least risk is followed, adoption of the first procedure for  $\bar{G}$  and the second procedure for PS,  $\bar{S}$ ,  $\bar{W}$  and  $\bar{D}$ . The coefficient of variation (C) of the effective rainy period is computed as:  $C = (\sigma \times 100) / \bar{G}$  [C is used in association with  $\bar{G}$  to compare its relative variation, as it represents the relative variation irrespective of the magnitude of  $\bar{G}$ ]. In the case of PS,  $\bar{S}$ ,  $\bar{W}$  and  $\bar{D}$  the magnitude of variation is primarily important in comparison with the relative variation (as will be appreciated in later sections), so only s.d. values are used.

#### Percentage crop failure years [A]:

(7) The arid situation (A) or percentage crop failure years or riskiness in crop production due to drought, is defined as the percentage number of years for which  $G < 5$  weeks. A 5-week period is considered to represent the minimum critical (reproductive) period with good moisture conditions for successful harvesting of a 98-day crop.

#### 3.2.3 Variables and their agronomic implications

The average available effective rainy period ( $\bar{G}$ ) defines the available growing period excluding the period that is available from the soil moisture reserve, which varies depending upon the soil type. This variable is associated with the type of cropping pattern, but is modified by variations in the onset and cessation times of effective rainy periods. <sup>The</sup> ~~This~~ variability <sup>in cropping pattern</sup> is defined by the s.d. of the commencement time of sowing rains ( $\delta$ ) and the duration of the available effective rainy period ( $C$ ). When  $\delta$  and  $C$  are large the dependability of that cropping system is very low. It follows that careful planning is necessary before any new system is adopted to such areas. The single most important operation is to determine the appropriate sowing time for optimum utilization of available soil water. The mean week of commencement time of sowing rains ( $\bar{S}$ ) is, therefore, an

---

<sup>1</sup>The boldface printing of  $\bar{G}$ ,  $\bar{S}$ ,  $\bar{PS}$ ,  $\bar{W}$  and  $\bar{D}$  respectively represent  $\bar{G}$ ,  $\bar{S}$ ,  $\bar{PS}$ ,  $\bar{W}$  and  $\bar{D}$  as in Figures and Tables of this Thesis

important factor in agricultural planning. The agricultural output at any location depends upon the level of inputs (e.g., fertilizers, weed management, cultural operations, etc.). However, it also depends upon the level of risk involved at a specific location. The aridity Index (A) presents a measure of such risk in terms of probable percentage crop failures.

Vertisols and associated soils in India cover  $\sim 73 \times 10^6$  ha (Fig. 3-1b), which constitute  $\sim 22\%$  of the total area of the country. These soils also occur extensively in northern Australia, Sudan, Ethiopia and in smaller areas of sub-Saharan Africa, particularly Chad and Tanzania. Smaller areas also occur in Mexico, central America, Venezuela, Bolivia and Paraguay (ICRISAT, 1981). Water-logging is a major problem in vertisols, which are characterized by low infiltration rates, but is not usually an important problem in most other soils. Primary tillage and seeding in these deep, cracked clay soils is difficult once the rains have commenced. With a few exceptions (Sudan, east Africa) they are generally left fallow during the rainy season and are cropped only in the post-rainy periods. This practice does not facilitate optimum utilization of natural resources for potential cropping and also increases runoff and soil erosion. The timing of tillage is the key to successful cropping, otherwise weeds become unmanageable and yields are substantially reduced.

Dry-seeding techniques, applied before the rains, may overcome these difficulties to a certain extent. Dry-seeding anticipates the commencement of rains by a few days and with the first rains the seed germinates. Dry-seeding is feasible where the onset time of rains is reliable and was found to be successful at the ICRISAT Centre. This technique is practiced by farmers in some parts of India, particularly in the Akola region.

The parameters discussed above may be very useful in assessing the agricultural variability of many parts of the SAT. The s.d. of commencement time of sowing rains ( $\delta$ ) can provide a measure of the likely suitability of dry-seeding in different regions. Similarly, the mean occurrence of wet spells ( $W$ ) can be used to assess the water-logging hazard at a specific location. Wet spells, along with the dry spells ( $D$ ), and their respective s.d. ( $\alpha$ ,  $\beta$ ) can be used to assess the suitability of a region for dry-land agriculture. These parameters can indicate the probable duration and variability of periods suitable for agricultural

operations within the rainy season. They can be used to assess the potential for runoff recycling to increase production, particularly in soils with low water-holding capacity and they can be used to estimate the duration of dry spells in relation to the growth patterns of specified crops.

### 3.3 COMPARATIVE ANALYSIS

The method outlined above [hereafter referred to as the R-method] is an extension of the concepts of Cocheme & Franquin (1967; CF-method) and Hargreaves (1974, 1975; H-method). The CF-method considers the moist period based on a normal monthly data set, while the R-method estimates the moist period on the basis of weekly data for individual years using a moving average technique. The H-method is based on rainfall probabilities for individual and independent months, while the R-method takes into account actual time sequences, year by year, over the entire moist period. The R-method, therefore, incorporates all the important and useful features of the CF- and H-methods, and it also gives some useful additional information. Table 3-1 presents these parameters for a few selected Indian stations. For example, in the case of Bangalore, the s.d. of  $G(o)$  is very high, but at Agra is very small. This example demonstrates an association between the indicator and the observed instability of food production at Bangalore compared with Agra. The variability over time of the commencement time of sowing rains is also wide ( $s$  is 4.7 weeks at Bangalore and 1.0 week at Agra). Consequently, while proper planning of the sowing time is very critical at Bangalore, it is much less so at Agra. In many years there is a possibility of crop failure at Bangalore ( $A = 32\%$  of the years) compared to Agra ( $A = 8\%$  of the years). At Bangalore, the instability of crop production can be reduced by proper management of water, through recycling of runoff during dry spells, as there is a possibility of obtaining useful runoff in many years [ $W \pm \alpha = 3.9 \pm 3.1$  weeks, ICAR, 1982].

On the red soils (alfisols) of Bangalore, only the late kharif (or rainy season) crop is successful (Singh et al., 1974; Spratt & Choudhury, 1978; ICAR, 1982). Crop production is stable at Agra compared to Bangalore, where planning of the sowing time (August or September) is most critical (irrespective of soil type). By comparison, the H-method suggests that crop production is stable at Bangalore, with one or two crops with  $MAI \geq 0.34$  for 6 months, while at Agra cropping is



Table 3-1 : Climatic classification results based on the present (R-method) approach.

Sl.No.	Station	$\bar{S}$	$\delta$	$\bar{G}$	$\theta$	$\bar{W}$	$\alpha$	$\bar{D}$	$\beta$	A
1.	Allahabad	25.1	1.4	16.5	3.5	7.0	2.1	5.3	2.0	0
2.	Indore	24.7	1.3	16.4	3.1	7.0	2.2	6.0	2.1	0
3.	Bangalore	27.4	4.7	11.8	8.4	3.9	3.1	5.2	3.9	32
4.	Agra	26.3	1.0	13.3	3.6	5.9	2.0	5.1	1.9	8
5.	Anantapur	35.5	4.8	5.2	5.4	2.7	1.7	3.7	2.5	52
6.	Jodhpur	29.0	2.1	2.6	4.4	2.9	1.1	3.3	2.1	73
7.	Ranchi	23.9	2.9	16.4	3.8	7.5	3.4	3.7	1.8	0

$\bar{S}$  = week No. (standard week)

$\bar{G}, \theta, \bar{W}, \alpha, \bar{D}, \beta, \delta$  = No. of weeks

A = Percentage No. of years

unstable and risky, having MAI  $\geq 0.34$  for 2 months only (Table 3-2). At Jodhpur, cropping intensity varies from 30% to 100%, while at Anantapur it ranges from 100% to 125% and in years of early rains double cropping could be practiced (as referred to above). The contrary is evident from Troll's (1965) approach (as modified by Reddy, 1977a) [Table 3-2], with 0 and 1 humid months at Anantapur and Jodhpur, respectively.

According to the CF-method, the difference between Allahabad and Indore is negligible (Table 3-2), and this is also evident from G [Table 3-1], but the R-method suggests, in addition, that the percentage of crop-failure years due to drought are zero at these places and the variation in the commencement time of sowing rains is small ( $\delta = 1.3$  to 1.4 weeks). Therefore, dry-seeding is feasible in the vertisol regions of Indore, whereby two crops could be grown (Spratt & Choudhury, 1978). Traditionally, however, only one crop is grown in the post-rainy season, on land fallowed during the rainy season, using stored soil water. Furthermore, there are significantly more field working days at Indore compared to Allahabad.  $W = 7.0$  and  $D = 6.0$  weeks at Indore, and they are respectively 7.0 and 5.3 weeks at Allahabad. These features facilitate the use of dry-land agriculture to grow crops like sorghum at Indore and paddy-rice at Allahabad (Fig. 2-3). For example, see also Ranchi [Ranchi comes under the sub-humid or wet-dry zone and Indore comes under semi-arid zone], where the dry spells ( $D = 3.7$  weeks) are far fewer than wet spells ( $W = 7.5$  weeks), and where dry-land agriculture is less productive, particularly in the vertisols region. Upland rice is the major crop in the vertisols region of Ranchi in the rainy season (Mohsin & Sinha, 1979; Fig. 2-3).

In India, a large proportion of regions with deep vertisols (Fig. 3-1b) are kept fallow during the rainy season and are cropped only in the post-rainy season (Table 3-3)<sup>2</sup>. It appears from Table 3-3 that the reasons for this practice are:

1. undependable timing of initial rains (high  $\delta$ ),
2. high water-logging problem with less available days for field work (high  $W$  along with low  $D$ ).

In the former case, proper identification of sowing times ( $S$ ) is critical for

---

<sup>2</sup>Compiled from the agricultural statistical publications of Government of India.

Table 3-2 : Climatic classification results based on various approaches.

Sl.No	Station (India)	Soil Type#	R'		T		C-F	
			(mm)	PE'	(months)	h	m	md
1.	Allahabad	Alluvial	1027	1537	3*	3*	95	120 175
2.	Indore	Black	1053	1813	3*	3*	100	120 155
3.	Bangalore	Red	924	1501	4*	6**	115	205 235
4.	Agra	Alluvial	765	1467	3*	2+	75	100 120
5.	Anantapur	Red	562	1857	0+	1+	0	90 200
6.	Jodhpur	Sierozem	380	1843	1+	0+	0	60 80
7.	Ranchi	Red	1463	1304	4*	4*	130	163 240

\* = semi-arid  
\*\* = sub-humid or wet dry  
+ = arid  
R' = Mean annual precipitation, mm  
PE' = Mean annual potential evapotranspiration, mm  
R'' = Mean monthly precipitation, mm  
R' = Mean monthly precipitation + stored soil water, mm  
PE = Mean monthly potential evapotranspiration, mm  
T = Troll's (1965) approach: No. of humid (R'' $\geq$ PE) months  
(as modified by Reddy, 1977a)  
H = Hargreave's (1971) approach: No. of months with MAI $\geq$ 0.34  
C-F = Cocheme & Franquin's (1967) approach:  
h = Humid (R $\geq$ PE) period, in days  
m = Moist (R $\geq$ 0.5PE) period, in days  
md = Moist-dry (R $\geq$ 0.25 PE) period, in days  
# Alluvial : Entisols  
Black : Vertisols  
Red : Alfisols  
Sierozem : Aridisols

Table 3-3 : Climatic attributes and percentage area under Kharif (Rainy season) fallow for selected locations in the deep vertisol regions of India.

Location	Agroclimatic Attributes*				Percentage area under kharif fallow
	$\delta$	$\bar{W}$	$\bar{G}$	A	
	Number of weeks			%	
<hr/>					
a: <u>Undependable rainfall zone</u> (with high $\delta$ -zone of erratic initial rains)					
Ahmednagar	4.9	3.4	9.2	33	57.3
Sholapur	4.0	3.6	11.3	24	74.3
Poona	4.1	3.6	12.1	15	44.0
Aurangabad	3.0	4.5	13.2	12	40.3
Hyderabad	2.9	4.2	12.9	13	25.0
b: <u>Dependable rainfall zone</u> (with high $\bar{W}$ - water-logging zone)					
Jabalpur	1.5	9.8	18.5	00	50.0
Indore	1.3	7.0	16.4	00	44.2

\*

$\delta$  = Standard deviation of commencement of sowing rains.

$\bar{W}$  = Mean number of wet weeks within the effective rainy period.

$\bar{G}$  = Mean number of effective rainy weeks.

A = Percentage crop failure years or riskyness in crop production due to drought.

crop production, and in the latter situation the problem can be reduced by dry-seeding where the timing of initial rains is rollable (where  $\delta$  is small). Dry-seeding is carried out a week before the onset of rains (again based on local forecasts), generally before  $S$  and after  $S - \delta/2$ . However, in the former case, sowing can be carried out after  $S$  and before  $S + \delta/2$  (based on local forecasts) [see experimental evidence for a few Indian locations, ICAR (1982)]. Bellary is a typical high  $\delta$  location, where a post-rainy season (or *rabi*) crop is more assured than a rainy season (or *kharif*) crop. The traditional sowing times at Bellary are not the best (Spratt & Choudhury, 1978), but yields could be increased by advancing the date of sowing to September (Singh et al., 1974). The mean week of commencement time of sowing rains ( $S$ ), week 35, agrees very well with this finding. Similarly, at Hyderabad, it was found that dry-seeding was successful with  $\delta = 2.9$  weeks, while at Sholapur, with  $\delta = 4.0$  weeks, it was a failure (Binswanger et al., 1980).

### 3.4 SUMMARY

A simple method for deriving agroclimatic variables to classify the semi-arid tropics into relevant agronomically homogeneous zones has been developed on the basis of actual time sequence of weekly rainfall and potential evapotranspiration data over periods of more than 15 years. A term 'available effective rainy period' is introduced for this purpose. The available effective rainy period is defined as the number of consecutive weeks in which the 14-week moving average of  $R/PE$  is  $\geq 0.75$ , but for the initial week the value of  $R/PE$  is  $\geq 0.50$ . The preceding week is taken to be the week of commencement time of sowing rains. The method permits estimation of wet and dry spells during the available effective rainy period and an estimate of the likely percentage of crop failure years. The individual yearly estimates are used to define the mean week of commencement time of sowing rains [ $S$ ] and its variability [ $\delta$ ]; the mean available effective rainy period [ $G$ ] and its variability [ $\theta$ ,  $C$ ]; the mean number of wet and dry weeks within the available effective rainy period [ $W$  and  $D$ ] and their variabilities [ $\alpha$  and  $\beta$ ]; and the percentage crop failure years or level of risk associated with dry-land agriculture [ $A$ ]. This procedure has been developed with special reference to the SAT. These variables can be used to define the most suitable farming systems for different regions of the SAT.

Determination of  $S$ ,  $PS$ , and  $\delta$ ,  $\gamma$  help to assess the feasibility of dry-soeding, proper period for sowing, land preparation, etc. Dry-soeding is less favourable where  $\delta$  is high.  $G$  and  $C$  play a significant role in planning the cropping patterns to be followed at a particular location. 'A' explains the risk associated in crop production and, therefore, input levels. Measurement of  $W$ ,  $D$  and  $\alpha$ ,  $\beta$  (i) help to determine the feasibility of runoff collection and its recycling during drought periods to reduce the risk; (ii) aid in assessing water-logging situation, intensity of soil erosion and in estimating the days available for field work, and thereby developing measures of soil management to overcome these problems; and (iii) also help to identify suitable crops. Therefore, these selected variables allow a more relevant and realistic assessment of agroclimatic environment and agricultural production potential of a selected location or region.

## CHAPTER 4

### AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS:

#### II. IDENTIFICATION OF CLASSIFICATORY VARIABLES

##### 4.1 INTRODUCTION

Some agroclimatic variables are only useful for agricultural planning, while others are mainly used in assessing agricultural production potential. These variables are identified using data obtained at 80 locations in India. However, for the transfer of location specific agricultural technology, it is important to understand the dissimilarities between agroclimatic variables associated with local orographic effects, regional effects, such as land-sea contrast and differences in circulation patterns, and the local effects of global circulation patterns. The identification of these variables, at different scales, is based on data from India and west Africa. The importance of some of these variables for crop production is assessed using broad soil types (alfisols and vertisols).

##### 4.2 DATA AND ANALYSIS

Climatic data represent point observations, but in practice they are treated as representing a region around that point. In reality, major variations are evident even at the local or micro-scale (Reddy, 1980). These variations are very important in micro-scale studies, but in macro-scale studies point observations are treated as being representative of a wide region, even with these limitations.

The basic data consist of observed weekly rainfall (R) and estimated potential evapotranspiration (PE). The rainfall data used in this study are weekly totals, derived ultimately from daily data. Weekly rainfall data from 80 locations in India (Fig. 4-1, Appendix D[A]) are obtained from the Indian Meteorological Department (IMD), Poona; west African data (59 locations in Senegal and 60 in Upper Volta) are obtained from ORSTOM, Paris (Fig. 4-2, Appendix D[B & C]). Recording periods vary from 15 to 70 years, but in most cases exceed 25 years. Data are verified and

checked after computerization. Observational errors, if present, are the responsibility of the respective agencies.

The monthly average PE values (primarily derived using Penman's (1948) approach) for India and west Africa are taken from Rao et al. (1971) and Reddy & Virmani (1980a), respectively. Weekly average PE values are obtained by graphical interpolation from monthly average values. Individual yearly PE values are computed from average PE, R and individual year R values using the Reddy's (1979a) method (for details see Appendix E).

Using the methodology discussed in Chapter 3, the nine agroclimatic variables ( $S$ ,  $\delta$ ,  $G$ ,  $C$ ,  $W$ ,  $\alpha$ ,  $D$ ,  $\beta$  and  $A$ )<sup>1</sup> are calculated for all 199 locations. Some, particularly those in south central India, show two rainy periods in some years. The first period of < 5 weeks comprises pre-monsoon thunderstorms and is less reliable than the second period. Thus, when computing these parameters, the intervening dry period is extended by not considering the first rainy period.

The spatial distribution of  $G$ ,  $C$ ,  $S$ ,  $\delta$ ,  $W$ ,  $\alpha$ ,  $D$ ,  $\beta$ , and  $A$  in India are depicted in Figs. 4-3 and 4-4 with the SAT boundary superimposed. In Figs. 4-3d and e, the vertisol boundary is also superimposed in order to assess some of the important dry land agricultural problems which are not important in other SAT soils. The results of the comparative analysis of different agroclimatic variables are presented in Figs. 4-5 to 4-8 which incorporate both Indian and west African data.

### 4.3 CROP PRODUCTION POTENTIAL [INDIA]

#### 4.3.1 Spatial distribution of agroclimatic variables

The standard deviation of  $S$  ( $\delta$ ) is very high over the Deccan plateau and for the extreme north western areas (Fig. 4-3d). For the former, bimodal rainfall zone, the high values of  $\delta$  are due to orography. This causes a high variation in the length of the dry period between the two rainfall peaks, and hence a very low suitability for crop production (Figs. 4-3b and 4-4). It is important, therefore, to differentiate between bimodal and unimodal rainfall stations, even if other factors are the same. The bimodal rainfall referred to here is different from that in east Africa

---

<sup>1</sup>For details on symbols see back of the Thesis.





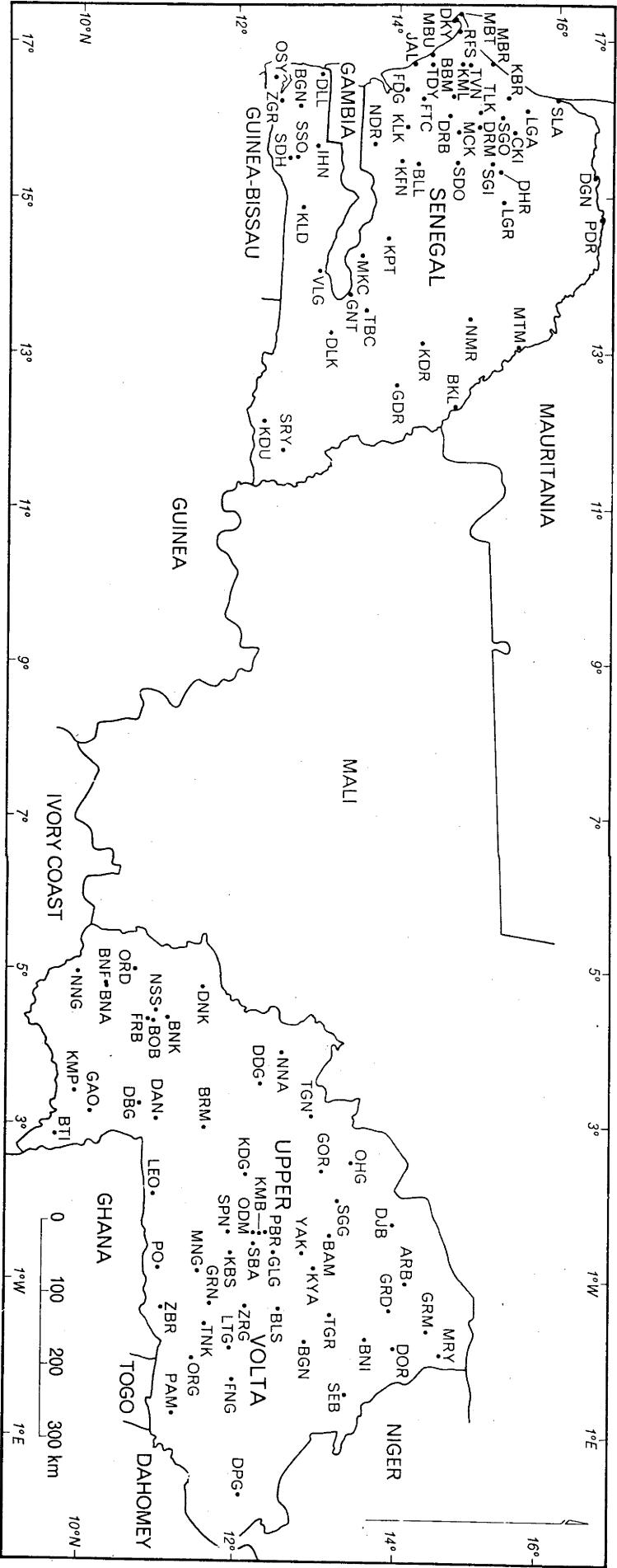


Figure 4-2 : Location of selected stations in Senegal and Upper Volta.

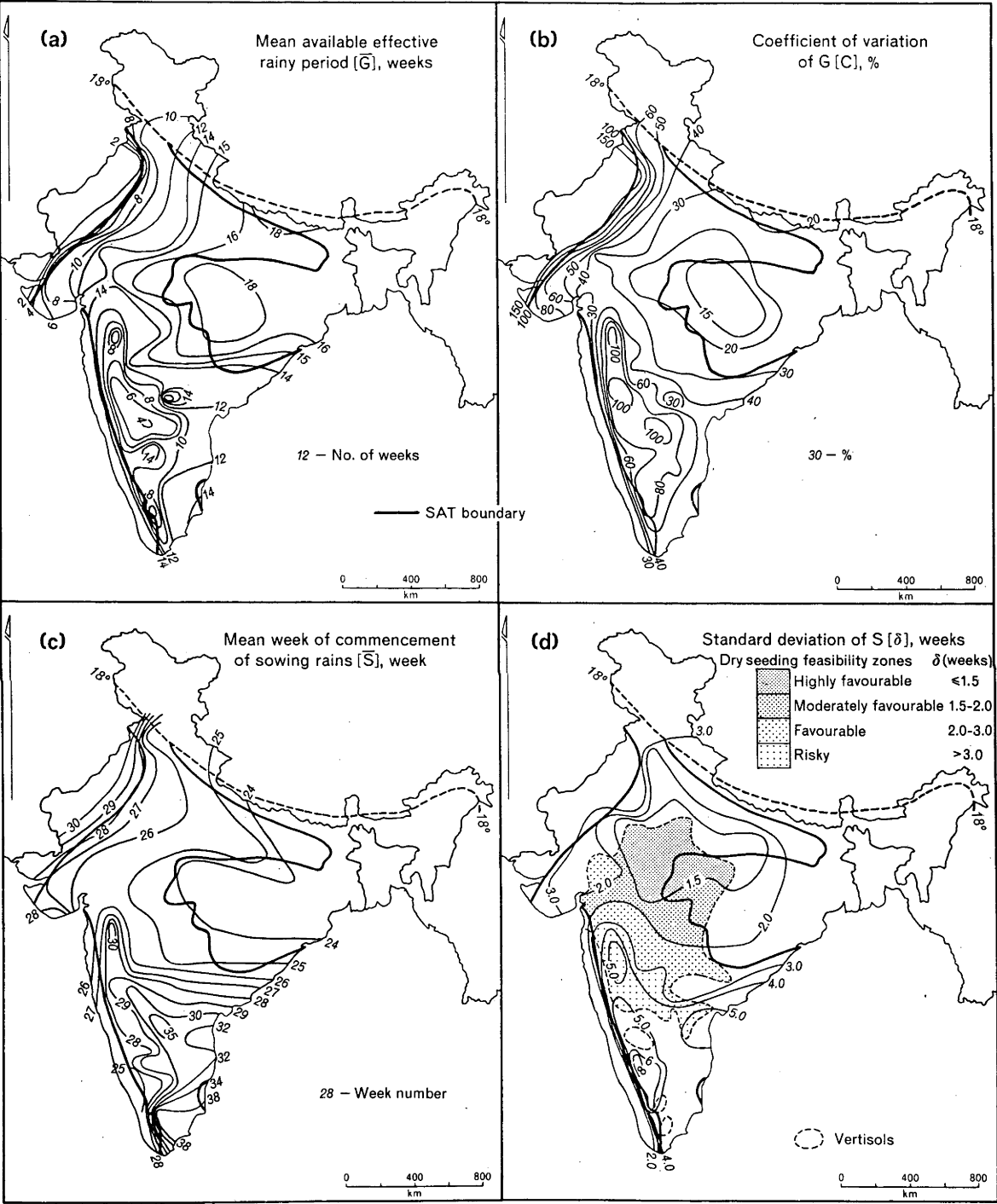
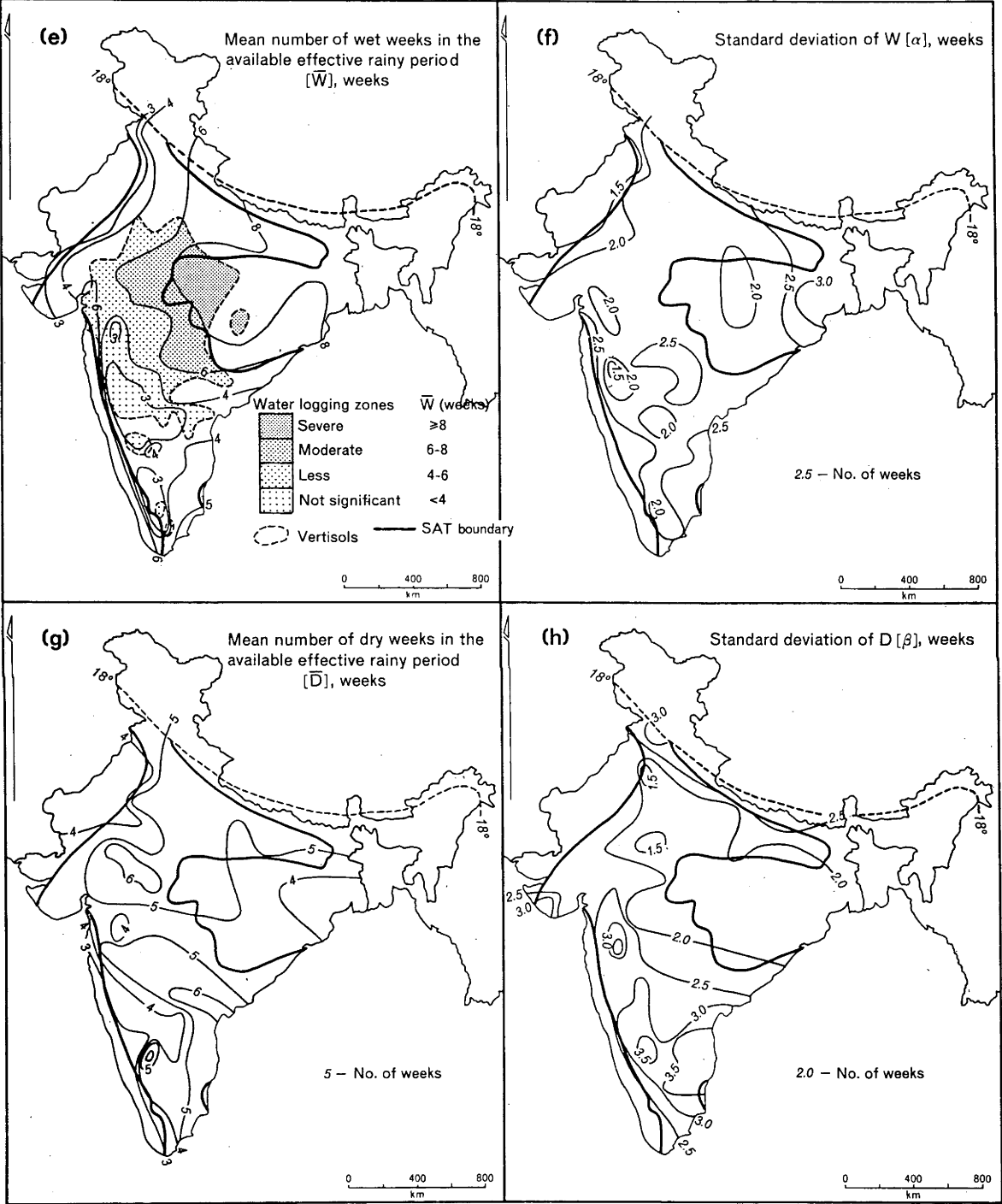


Figure 4-3 : Spatial distribution of agroclimatic attributes.



Cont.

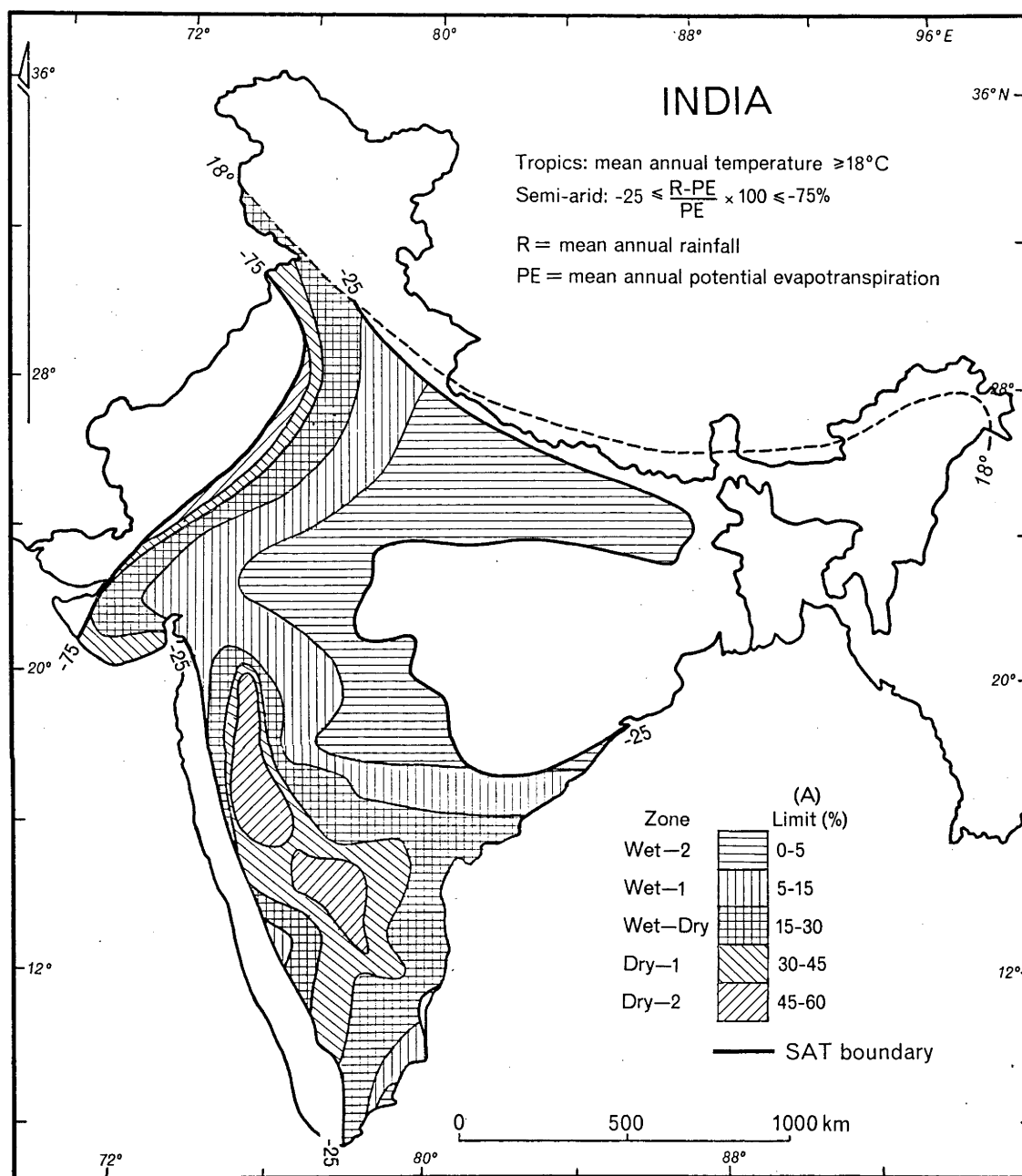


Figure 4-4 : Spatial distribution of the percentage crop failure years or percentage years with  $G \leq 5$  weeks (A).

(e.g., see Biodova in Somalia) where the two peaks are separated by a long dry spell and in fact represent two separate cropping seasons. The high value for  $\delta$  over south India indicates that careful planning is needed for sowing operations, with the most appropriate week shown in Fig. 4-3c. This agrees very well with experimental findings at some of the locations (ICAR, 1982). In south India the available effective rainy period decreases from the east to the northwest (Fig. 4-3a) and the associated risk decreases in the same direction (Figs. 4-3b and 4-4).

In the 500-1250 mm mean annual rainfall zone (SAT) of north India,  $G$  varies from 4 to 16.5 weeks (Fig. 4-3a), with  $C$  varying from 15% to 150% (Fig. 4-3b). The reliability of the moist period decreases gradually from the east to the west, but this pattern is not so systematic in the south. In the north, the wet spells (Figs. 4-3e and f) gradually decrease from the east to the west while dry spells (Figs. 4-3g and h) gradually increase from the east to the west. Because of this pattern, the western parts of India are more suitable for dry-land agriculture, compared to the eastern parts of north India which fall within the sub-humid zone where upland rice is the major crop in the rainy season. Regions with crop failure years ( $A$ ) more than 60%, which occur mainly in the arid zone (Fig. 4-4), are generally unsuitable for food crop production (Singh, 1974; ICAR, 1982).

#### 4.3.2 Dry-seeding feasibility zones

Dry-seeding is feasible only when the onset of sowing rains is stable over the years, i.e., the variation in the commencement time of sowing rains,  $\delta$ , over the years must be small. Seed placed in dry soil may not remain viable for long under high soil temperature conditions. An arbitrary limit of 20 days is used here, so that if  $\delta$  exceeds 20 days then dry-seeding may not be feasible. Regions that are suitable for dry-seeding in India can be delineated using this basic criterion. The spatial distribution of  $\delta$  are superimposed on the vertisols and are presented in Fig. 4-3d. The vertisol areas of India are divided into four major zones according to their suitability for dry-seeding and these zones are shown in Fig. 4-3d. For example, those regions surrounding Indore are highly favourable for dry-seeding. Akola and its surrounding area is next in order, but at present a major part of this region is kept fallow. These results suggest that the regions mentioned above have considerable potential for the introduction of dry-seeding technique (Spratt & Choudhury, 1978; ICAR, 1982).

#### 4.3.3 Water-logging zones

The length of wet spells ( $W$ ) in the available effective rainy period ( $G$ ), superimposed on vertisol regions of India and four probable zones, are presented in Fig. 4-3e. The water-logging problem is considered insignificant if  $W < 4$  weeks. The major part of the area of severe hazard lies in the sub-humid zone, where paddy-rice is the major crop (Fig. 2-3). Water-logging is not significant in the undependable rainfall zone with longer intermittent dry spells (Fig. 4-3g). Where  $\alpha$  is large, water-logging is also significant (Fig. 4-3f) at locations with  $W < 4$  weeks in some years.

#### 4.3.4 Risk in agricultural production

In agricultural production generally the input level depends upon the associated risk and socio-economic conditions. The aridity index ( $A$ , the percentage crop failure years) can be used to assess agricultural risk, although edaphic factors can modify these risk levels. Thus, risk may be relatively high in alfisols but lower in vertisols. In this study, the average risk at a specific location is presented irrespective of soil type.

Five zones are identified according to the level of risk ( $A$ ), as shown in Fig. 4-4. In the wet-2 zone, the variations in  $G$ ,  $C$  and  $A$  are small and the variations in  $\delta$ ,  $W$ , and  $D$  are wide (Fig. 4-3). The major problems are water-logging and soil erosion (Fig. 4-3e). At some locations in the wet-1 zone,  $C$  and  $\delta$  (Figs. 4-3b and d) are highly variable. In the wet-dry zone, crops fail in 16%-30% of the years, as the possibility of mid-season droughts occurring is greater [ $W > D$ , Figs. 4-3e and g]. In the dry-1 zone crops fail 31%-45% of the years. Water-logging is not an important problem (Figs. 4-3e and g). In the dry-2 zone crops fail in 46%-60% of the years. These regions represent the major drought-prone areas in the Indian semi-arid tropics. Sowing time is critical (Fig. 4-3d).

#### 4.3.5 Production parameters

The above groups are not at all homogeneous with regard to potential crop production, and the preceding discussion demonstrates that a single or a few variables can not explain wide variations in the climate, even on a regional scale. Agroclimate may appear similar in two locations with regard to some variables, but can differ widely with regard to others, causing farming practices to be entirely different. The following variables

are the most useful in delineating relevant agroclimatic parameters and production potential.

S and  $\delta$ : S is a time parameter and thus relates more to planning strategy than production potential;  $\delta$ , on the other hand, is related to production potential because it gives a measure of suitability for dry-seeding.

G, C and A: these relate to the possible cropping patterns and associated risks, and in several ways concern production potential.

W, D,  $\alpha$  and  $\beta$ : these relate to the probable crops; and problems and hazards associated with the particular system of farming, such as water-logging, that influence production potential as well as agricultural planning strategies, e.g., collection and recycling of runoff water, land management, etc.

All 9 variables are significant for delineating agroclimate and 8 [omitting S] are equally relevant for estimating production potential.

#### 4.4 COMPARATIVE ANALYSIS [INDIA, SENEGAL AND UPPER VOLTA]

##### 4.4.1 Zones with similar mean annual rainfall

##### 4.4.1.1 Local and regional differences

India: Table 4-1 presents the data from derived agroclimatic variables for selected locations in India under three groups of mean annual rainfall. Within the first group (low rainfall SAT), the results show wide differences between Ajmer and Bijapur. Bijapur is in a less reliable zone [ $\delta$  = 3.7 weeks and C = 100%] than Ajmer [ $\delta$  = 1.5 weeks and C = 67%], and this requires more careful selection of sowing times. The risk is 53% at Bijapur and 30% at Ajmer.

Four stations are included in the next group (medium rainfall SAT), two each from Andhra Pradesh (Hyderabad and Cuddapah) and Maharashtra (Jalgaon and Sholapur). At all these locations most of the deep vertisols are kept fallow during the rainy season and are cropped on residual soil moisture in the post-rainy season (ICRISAT, 1981). This is due to high variability in the commencement time of sowing rains [ $\delta$  > 4 weeks] at sholapur and Cuddapah, and water-logging problems at Jalgaon and Hyderabad [W > 4 weeks]. However, dry-seeding is feasible at Jalgaon and Hyderabad [ $\delta$  < 3 weeks]. Research station results indicate that with dry-seeding and proper management of the soil, it is possible to



Table 4-1 : Climatic attributes for selected locations in India  
(dependable and undependable rainfall areas).

LOCATION	RAINFALL <sup>*</sup> (mm)	TYPE*	AGROCLIMATIC ATTRIBUTES <sup>@</sup>				
			$\bar{S} \pm \delta$	$\bar{G} \pm C$	$\bar{W} \pm \alpha$	$\bar{D} \pm \beta$	A
<u>Low rainfall</u>							
Ajmer	523	1	27.3+1.5	7.6+ 67	3.6+1.8	3.7+2.1	30
Bijapur	565	2	32.3+3.7	6.0+107	2.9+2.3	4.0+3.0	53
<u>Medium rainfall</u>							
Jalgaon	775	1	25.3+2.2	12.8+ 36	5.0+2.4	4.4+1.9	7
Cuddapah	752	2	31.0+5.1	10.5+ 71	3.6+2.5	5.0+3.7	30
Hyderabad	783	1	27.2+2.9	12.9+ 45	4.2+2.5	5.0+2.5	13
Sholapur	755	2	27.9+4.0	11.3+ 57	3.6+2.0	5.1+3.0	24
<u>High rainfall</u>							
Agra	824	1	26.3+1.0	13.3+ 27	5.9+2.0	5.1+1.9	8
Bangalore	827	2	27.4+4.7	11.8+ 71	3.9+3.1	5.2+3.9	32

\* 1 = dependable & 2= undependable

@  $\bar{S} \pm \delta$  = Mean week of commencement of sowing rains  $\pm$  its standard deviation.

$\bar{G} \pm C$  = Mean available effective rainy period  $\pm$  its coefficient of variation.

$\bar{W} \pm \alpha$  = Mean number of wet weeks within the effective rainy period  $\pm$  its standard deviation.

$\bar{D} \pm \beta$  = Mean number of dry weeks within the effective rainy period  $\pm$  its standard deviation.

A = Percentage crop failure years (% number of years with  $G \leq 5$  weeks).

$\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$  and  $\beta$  are number of weeks; C is %; and  $\bar{S}$  is standard week number.

\* Mean annual rainfall

produce a kharif crop in the vertisols of Hyderabad but this is still risky at Sholapur (Binswanger et al., 1980). At all these stations water-logging is a problem in many years [ $W > 3.6$  weeks].

Similar problems concern the third group (high rainfall SAT), with Bangalore being located in an undependable rainfall zone [ $s = 4.7$  weeks and  $C = 71\%$ ] and Agra in a dependable rainfall zone [ $s = 1.0$  weeks and  $C = 27\%$ ]. At Bangalore the high variation between the different variables [ $S \pm s = \text{week } 27.4 \pm 4.6$  weeks and  $G \pm \theta = 11.8 \text{ weeks} \pm 71\%$ ] suggests a widely fluctuating long-term growing season. However, runoff recycling will substantially increase productivity [ $W \pm \alpha = 3.9 \pm 3.1$  weeks] in many years. Studies have indicated that at least 30% of annual rainfall is lost through runoff on lands with 1.5–2.0% slopes. There is a good opportunity for harnessing this surplus (ICAR, 1982). Dry-seeding is feasible at Agra but is risky at Bangalore. Water-logging is a problem in many years at both locations [ $W > 3.6$  weeks and  $\alpha > 2.0$  weeks].

The large differences in agroclimatic variables in India are mainly associated with local scale orographic and regional circulation patterns. These differences have significant influence on crop productivity.

#### 4.4.1.2 Regional and continental differences

**India, Senegal and Upper Volta:** Table 4-2 presents climatic variables relating to India, Senegal and Upper Volta under four mean annual rainfall groups, varying from 550 to 1350 mm. Table 4-1 shows that the variable means, particularly  $G$ , are very similar within groups, but that the variations of  $s$  and  $C$  are considerable. Table 4-2 shows that even the mean values can show considerable differences when similar rainfall groups are compared over different continents. The effective rainy period and both wet and dry spells are longer in west Africa than in India under similar rainfall conditions. It can therefore be expected that the crops suited to these similar rainfall zones are somewhat different, and indeed this is the case; in west Africa, longer duration crops perform better. In addition, because of the longer dry spells and proportionately shorter wet spells during the available effective rainy period in west Africa, compared to India, the crop varieties selected should be more drought tolerant at different stages of growth. Dry-seeding is feasible in almost all zones of west Africa.

These results demonstrate the differences in agroclimatic variables in association with continental differences in general circulation patterns, which play significant role in the crop production potential.

Table 4-2 : Climatic attributes for selected locations in India, Senegal and Upper Volta.

			AGROCLIMATIC ATTRIBUTES <sup>@</sup>				
LOCATION	COUN-* TRY	RAINFALL (mm)	$\bar{S}_{+}\delta$	$\bar{G}_{+}C$	$\bar{W}_{+}\alpha$	$\bar{D}_{+}\beta$	A
<u>Low rainfall:</u>							
Bijapur	1	565	32.3+3.7	6.0+107	2.9+2.3	4.0+3.0	53
Sagata-Louga	2	538	29.2+1.8	12.6+ 45	4.2+2.0	5.6+1.7	13
Djibo	3	567	28.7+1.9	11.0+ 53	3.4+1.6	4.5+2.3	14
<u>Medium rainfall:</u>							
Cuddapah	1	752	31.0+5.1	10.5+71	3.6+2.5	5.0+3.7	30
Kidira	2	752	26.6+1.7	17.9+20	6.6+2.6	6.6+2.0	0
Boulsa	3	751	24.7+1.5	17.4+20	5.1+2.4	5.8+2.2	0
<u>High rainfall:</u>							
Dhar	1	953	25.1+1.4	16.5+21	7.0+2.1	5.3+2.0	0
Dialakoto	2	956	24.4+1.9	21.7+18	9.3+2.9	7.2+2.0	3
Dedougou	3	954	23.2+1.5	20.5+10	7.5+2.3	6.0+1.6	0
<u>Very high rainfall:</u>							
Jabalpur	1	1374	23.6+1.5	18.5+14	9.8+2.1	5.3+1.7	
Diouloulou	2	1388	25.8+1.8	21.3+14	10.0+2.7	6.3+1.2	0
Niangoloko	3	1331	20.5+2.3	26.3+11	10.5+2.6	7.0+1.7	0

\* 1 = India; 2 = Senegal; 3 = Upper Volta

@ As explained in Table 4-1.

The results presented in Tables 4-1 and 4-2 reveal the dangers inherent in the use of mean annual rainfall as a basis for interpreting agricultural productivity and for grouping locations.

#### 4.4.2 Interrelationships between different variables

In order to understand and characterize the above mentioned dissimilarity characteristics of global, regional and local scale associated with global and regional circulation patterns, land-sea contrast and orography, etc., a regression approach is followed. Figures 4-5 to 4-8 depict, respectively, the relationships of C v. G, W and D v. G, D v. W, C v.  $\delta$  for (a) India, (b) Senegal and (c) Upper Volta. The first four show a non-linear, and the last pair a linear relationship. Non-linear functions are fitted to the first four data sets and the best fit is presented in the respective figures for each set of variables. A linear function best fits the last set of variables and this is shown in Fig. 4-8. All except the last set have solutions significant at < 5% level.

##### Variation of C with G:

The best-fit solution to all data sets presented in Fig. 4-5 are:  $G = 2.0 + 500/(C+10)$ . The same equation is found to be valid for all three countries. The fitted curve from this equation is shown by a solid line. [While fitting this equation it is assumed that the lowest value that C can take is about 10%.] In India the dispersion around the curve is large compared with west Africa. The stations to the left of the curve are more dependable, i.e., the crop growing period is stable compared with stations to the right of the curve. The degree of dependability decreases as the station distances increase from left to right of the curve. In the case of India, most of the points on the right of the curve are stations that are in the rain shadow zone of the western Ghats. In west Africa the terrain is uniform and such orographic effects do not occur.

##### Variation of W and D with G:

The best-fit equations for the data presented in Fig 4-6 are:  $G = a + b/(W+b)$  and  $G = a \exp(bD)$ . However, the coefficients for different countries are different in these cases. The predicted curves are depicted by solid lines. For India, the two curves, i.e., W v. G and D v. G intersect at  $G = 13.3$  weeks and  $W = D = 4.7$  weeks, while for west Africa they intersect at somewhat higher values, i.e., for Senegal  $G = 17.8$  weeks and for Upper Volta  $G = 19.4$  weeks with  $W = D = 6.4$

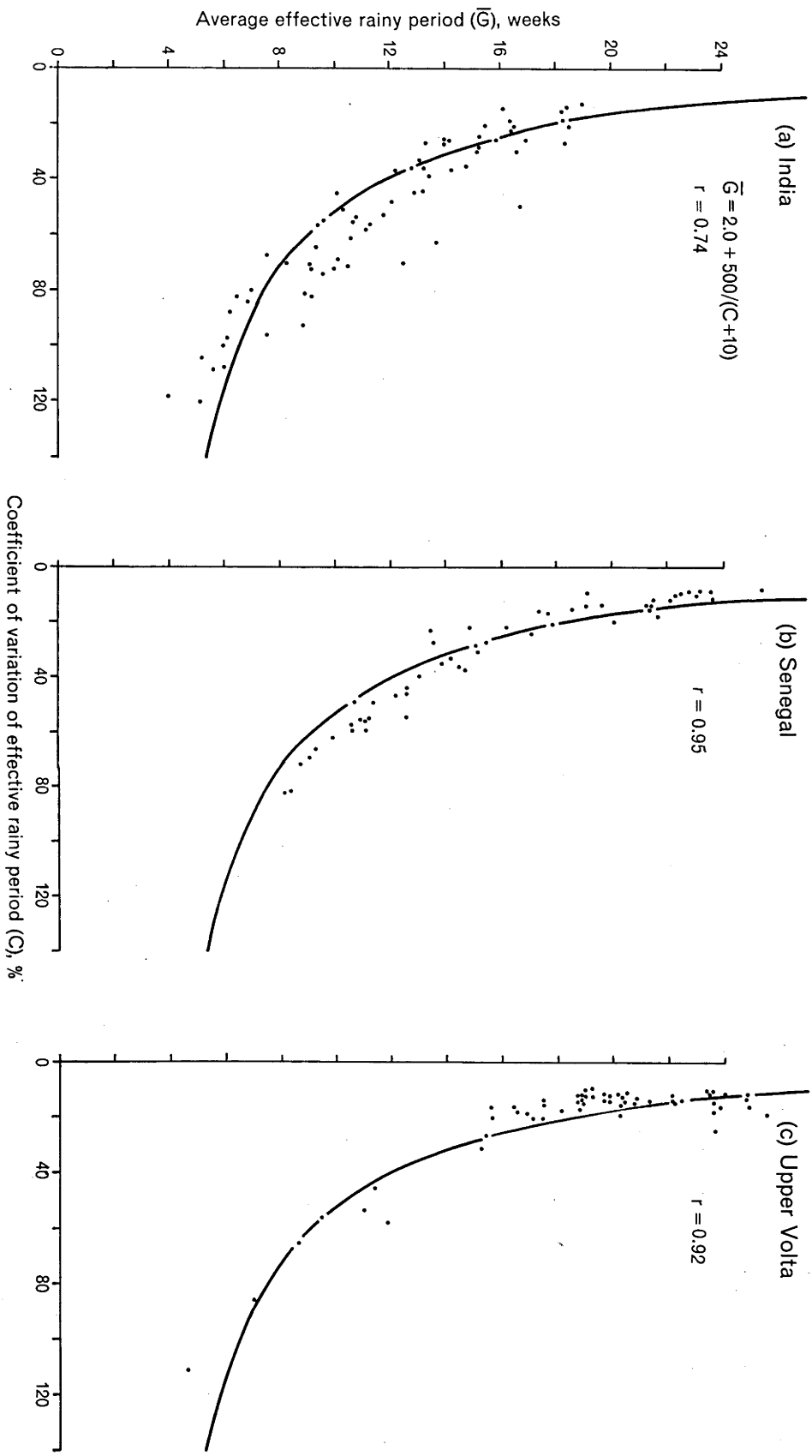


Figure 4-5 : Variation of the average effective rainy period ( $\bar{G}$ ) with the coefficient of variation of the effective rainy period (C) for India, Senegal and Upper Volta.

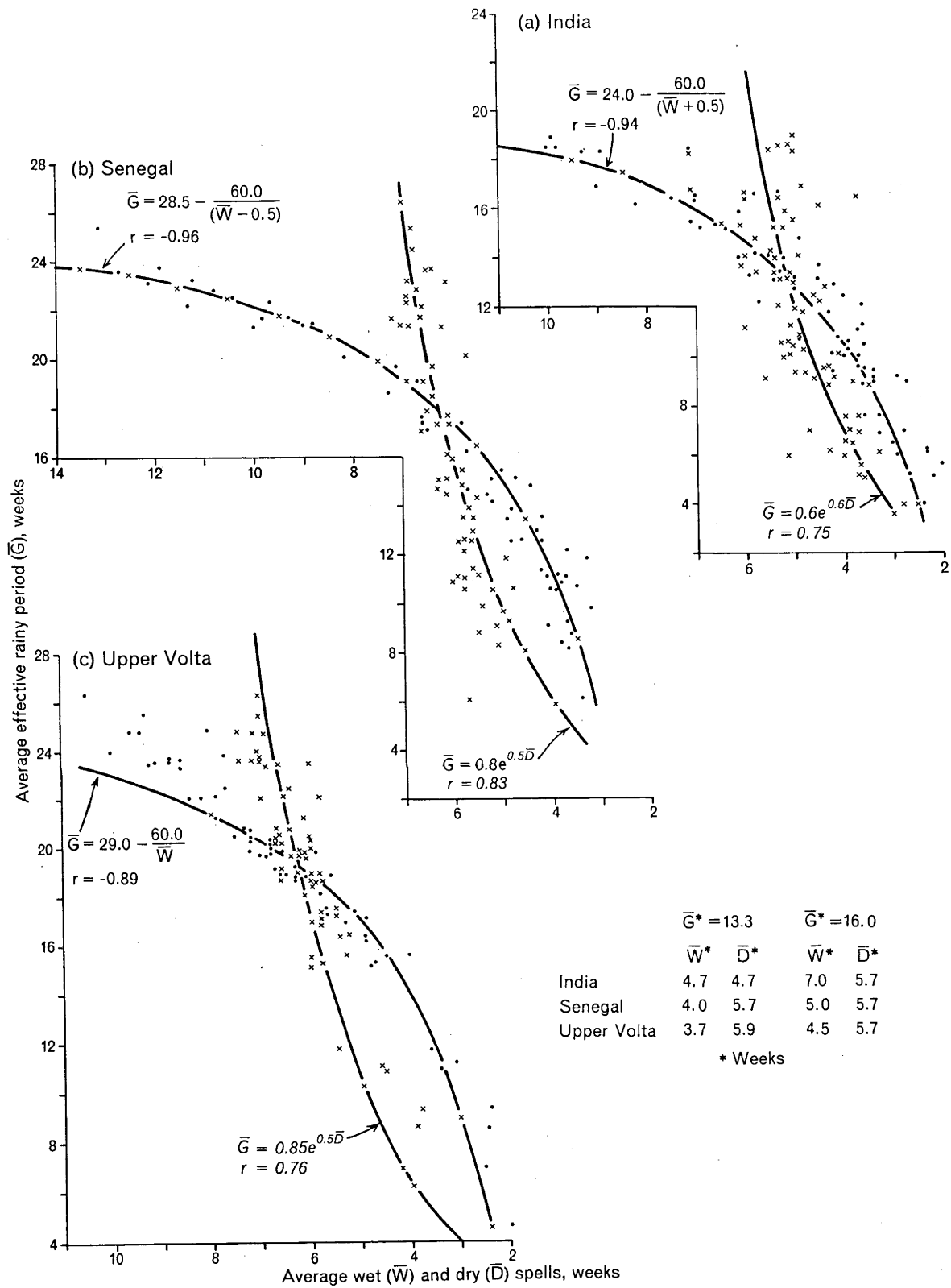


Figure 4-6 : Variation of the average effective rainy period ( $\bar{G}$ ) with the average wet ( $\bar{W}$ ) and dry ( $\bar{D}$ ) spells within the effective rainy period in India, Senegal and Upper Volta.

weeks<sup>2</sup>. The large differences in these limits between India and Upper Volta are mainly associated with the global circulation patterns, and the differences between Senegal and Upper Volta are associated with regional factors, such as land-sea contrast.

From Fig. 4-6 it is seen that for higher values of  $W$ ,  $W/G$  is large for India, followed by Senegal and then Upper Volta, while at lower values of  $W$ ,  $W/G$  is higher for Senegal, followed by India and the Upper Volta. This relationship is similar for  $D$ , where  $D/G$  is large for Senegal, compared with India and Upper Volta (neglecting the lower intersection, this range represents an arid situation only). This means that at stations in India, with the same mean annual rainfall (Table 4-2), the growing season is shorter, but the proportionate wet spells are larger and dry spells are less at higher values of  $G$ . Because of this situation, the number of fieldwork days are less and water-logging is a major problem under the same growing season.

#### Variation of $D$ and $W$ :

The best fit equation for the data sets of Fig. 4-7 is:  $D = a + b(W+d)$ . The curves are depicted by solid lines. The other coefficients ( $b$  and  $d$ ) are the same for the three countries (Fig. 4-7). In these figures a line passing through the origin with  $W = D$  is also depicted. It can be seen that this line meets the curves at 5.4 and 6.4 weeks for India and west Africa respectively. At stations above the straight line, water-logging is a problem and for the stations below, mid-season droughts are common. The latter situation is evident at many locations in India.

#### Variation of $C$ and $\delta$ :

The pattern of  $C$  v.  $\delta$  is depicted in Fig. 4-8. This figure indicates that the pattern of variation of  $\delta$  with  $C$  is not the same for west Africa and India. In west Africa, the variation of  $\delta$  with  $C$  is very small even for large values of  $C$  (which reflects the regular onset and irregular cessation times of effective rainy period). In India, the plot shows a cone shape with the point near the origin, suggesting wide variation, not only of the onset but also the cessation time of the effective rains. The points on the

---

<sup>2</sup>It appears that these intercepts indirectly relate to the varietal differences in crop species in terms of their adopted durations over India and west Africa. In India the common crop species in kharif are of short- to medium duration while in west Africa they are medium to long duration varieties in the SAT.

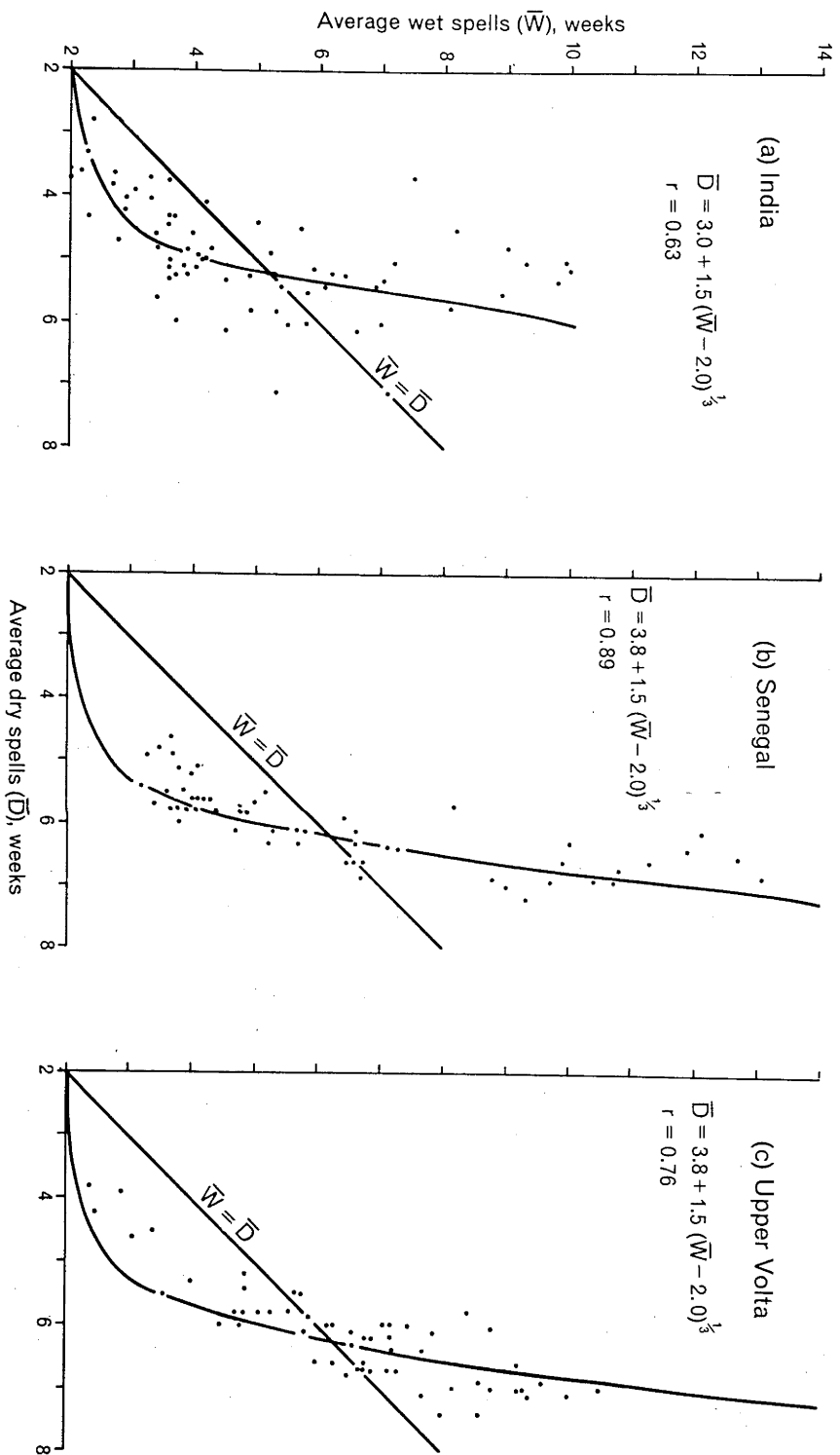


Figure 4-7 : Variation of the average wet spells ( $\bar{W}$ ) with the average dry spells ( $\bar{D}$ ) within the effective rainy period for India, Senegal and Upper Volta.



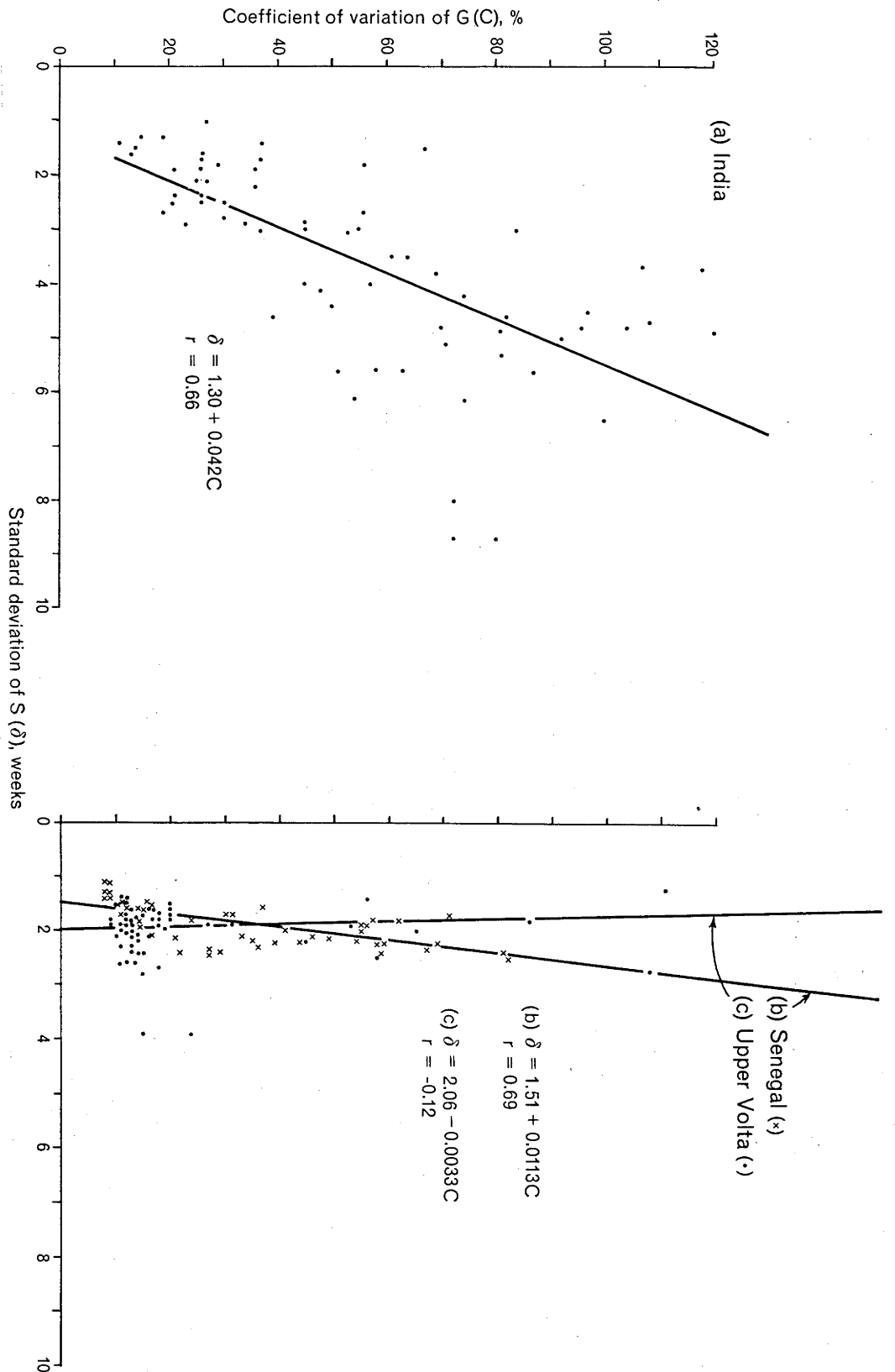


Figure 4-8 : Variation of the coefficient of variation of G (C) with the standard deviation of S (δ) for India, Senegal and Upper Volta.

far left of the best-fit curves (Fig. 4-8) represent locations with a long-term high variation in the cessation time, and the points to the far right of this line represent locations with a high variation in the onset time of sowing rains. Therefore, the cessation times of the effective rainy period is highly variable in west Africa, and both cessation and onset times are highly variable in India.

#### 4.4.3 Dissimilarity parameters

The above results show that even when mean annual rainfalls are similar in tropical semi-arid environments, agricultural production potential and the associated risks can be very different for various regions. These differences are associated mainly with orographic effects at local scale, circulation patterns at regional scale and general circulation patterns at continental scale. With the same value of  $G$ , considerable differences in  $\delta$  and  $C$  are seen in India where orographic effects play a major role. When these effects are compared at continental scale, even  $G$  itself showed wide variation and the proportion of  $W$  v.  $G$  changed substantially for different continents. This inference has a bearing on farming systems in general and cropping pattern in particular. Comparison of different variables between different continents make it possible to estimate the continental, regional, or local variation of agroclimatic variables. For example, from  $C$  v.  $G$ , the parameters that refer to local or regional effects are defined as:

$$G' = G^* - G$$

where  $G^*$  is the value estimated from the equation

$$G^* = 2.0 + 500/(C+10)$$

where  $C$  is the value corresponding to  $G$  and  $G'$  represents variable 9 (8 variables represent production potential parameters identified in an earlier section), accounting the regional and local scale dissimilarities.

Similarly, from  $W$  and  $D$  v.  $G$ , the parameters representing continental dissimilarities are defined as:

$$W' = W - K, D' = D - K$$

where  $K$  is the intersect point shown in Fig. 4-6, i.e., 4.7 and 6.4, respectively, for India and west Africa. The value of  $K$  define the relative water-logging or drought situations in the different continents.  $W'$  and  $D'$

represent variables 10 and 11 that can be used in the agroclimatic classification (Chapter 6).

The three above mentioned variables  $G'$ ,  $W'$  and  $D'$ , therefore, indicate the dissimilarities associated with differences at local, regional or continental scale, and are characterized as dissimilarity parameters.

#### 4.5 SUMMARY

Of the two climatic parameters used to compute the agroclimatic variables, rainfall comprises the observed data set and potential evapotranspiration represents an estimate from other climatic data. Both represent point observations.

SAT in India is delimited by 4-16.5 weeks mean available effective rainy period ( $G$ ) and with  $< 60\%$  of crop failure years ( $A$ ). The spatial distribution of the 9 agroclimatic variables in India, suggest that 8 of them could be used in connection with agricultural production & planning strategies and the remaining one ( $S$ , the mean week of commencement time of sowing rains) is useful for planning strategies in SAT India.

Some variables have simple and direct relationships with each other, but this is in appearance only. The deviations of these parameters from an average pattern have different implications in terms of farming system practices in general and cropping patterns in particular. Therefore, it is always better to consider as many variables as possible in the evaluation of climatic data.

The basic difference between the Indian and west African situations is that for similar mean annual rainfall, the corresponding effective rainy period is longer in west Africa. Accordingly, the other variables relating to the effective rainy period are significantly different. Orographic or local effects are greater in India compared with west Africa, where the terrain is more uniform. However, in west Africa there are regional differences associated with the land-sea contrast. West African stations show wide variations in the cessation times of effective rainy period, while in India this is the case for both cessation and onset times.

Regression analysis has been used to identify differences between locations at different scales, i.e., local differences caused by orography, regional differences associated with circulation patterns and continental differences associated with general circulation patterns. Using the data of 8 variables from 199 locations in India, and two west African countries

(Senegal and Upper Volta) three dissimilarity parameters were derived. Thus, of the 11 agroclimatic variables for classification of the SAT into the relevant agronomically-homogeneous zones, 8 can be used in connection with productivity potential and three can be used to identify dissimilarities in scale. All these variables will have significant influence on farming systems in general, and on the identification of adopted crops and cropping systems in particular.

## CHAPTER 5

### AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS:

#### III. CHARACTERISTICS OF VARIABLES RELEVANT TO CROP

##### PRODUCTION POTENTIAL

### 5.1 INTRODUCTION

The objective of this part of the study is to characterize the agronomic significance of selected variables by comparison with crop performance at selected locations. A soil-water balance simulation is used to assist in this analysis. Estimates of soil-water balance are useful in several ways for solving agricultural problems, for example, in the development of agroclimatic models for establishing the length of crop growing seasons. The soil-water balance estimates allow a more predictive approach to land and water management problems by adjusting crops to climate and, at a given site, permits assessment of different fallow-crop strategies. It is useful in the development of yield-forecasting models, which can help in the interpretation of the considerable variability in crop yields between seasons and regions, and in the monitoring of supplementary irrigation requirements and runoff modelling. All of these aspects may be important for the efficient management of agricultural systems at a particular site. Hence, a realistic method of computing soil-water balance, taking into account all the physical processes involved, and which can be used under diverse climatic, soil and crop conditions, is essential.

A large number of models have been developed during the past two decades aimed at predicting soil-water balance parameters, such as, evapotranspiration, runoff and soil moisture status over time intervals of 1-7 days.

Reddy (1983a) reviewed the literature and developed a simple model (ICSWAB) that has been found to work well over diverse climatic, soil and crop conditions. It computes evapotranspiration as a function of time after wetting of the soil, giving consideration to subsequent precipitation by

using readily available meteorological data (rainfall and open-pan evaporation). The growth stage of a crop is represented by coefficients based on leaf area index (LAI) and percentage light interception. This procedure permits the model to account for the available water at different stages of crop growth. Details on the computational procedures in Basic-plus computer language have been presented by Reddy (1979a). The practical application of the procedure in crop production studies have been presented for agroclimatic modelling (Liu, 1977; Reddy et al., 1977, 1982; Reddy, 1979b; Binswanger et al., 1980), yield stability (Rao & Willey, 1980), runoff assessment (Ryan et al., 1982) and supplementary irrigation scheduling (Reddy, 1983b). It has also been found that its utility in yield forecasting models is high (Fig. 5-1). In SORGF (Arkin et al., 1976) the soil-water balance is computed using the model of Ritchie (1972) and Reddy (1983a), and its (SORGF) ability to predict grain and dry matter yields for 23 data sets has been verified for five sorghum cultivars in both kharif and rabi seasons during 1979 and 1980 (details on data sets are presented by Huda, in *Agroclimatology Annu. Rep.*, 1980-81, ICRIASAT, India). With Ritchie's (1972) model the root-mean-square errors (RMS) and correlation coefficients ( $r$ ) for dry matter and grain yields are 2758 and 1739 kg/ha, and 0.35 and 0.37, respectively. The corresponding values with Reddy's (1983a) model are 1506 and 849 kg/ha, and 0.85 and 0.81. In the latter model the parameter used to predict yields was actual evapotranspiration (AE) relative to open water (E).

## 5.2 METHOD AND ANALYSIS

The daily soil-water balance equation is generally written in the form (Slatyer, 1967):

$$\Delta M_n = R_n - AE_n - RO_n - D_n$$

where  $R_n$ ,  $AE_n$ ,  $RO_n$ ,  $D_n$  and  $\Delta M_n$  represent rainfall or irrigation, actual evapotranspiration, surface runoff, deep drainage, and soil moisture change on day  $n$ , respectively.  $\Delta M_n = M_n - M_{n-1}$ , where  $M$  represents the soil moisture on any day  $n$  or  $n-1$ . In the above equation the component AE can be determined using the procedure of Reddy (1983a).

The soil-water balance is simulated using data from Jodhpur in the arid zone, and Anantapur, Bangalore, Sholapur, Hyderabad, Akola and

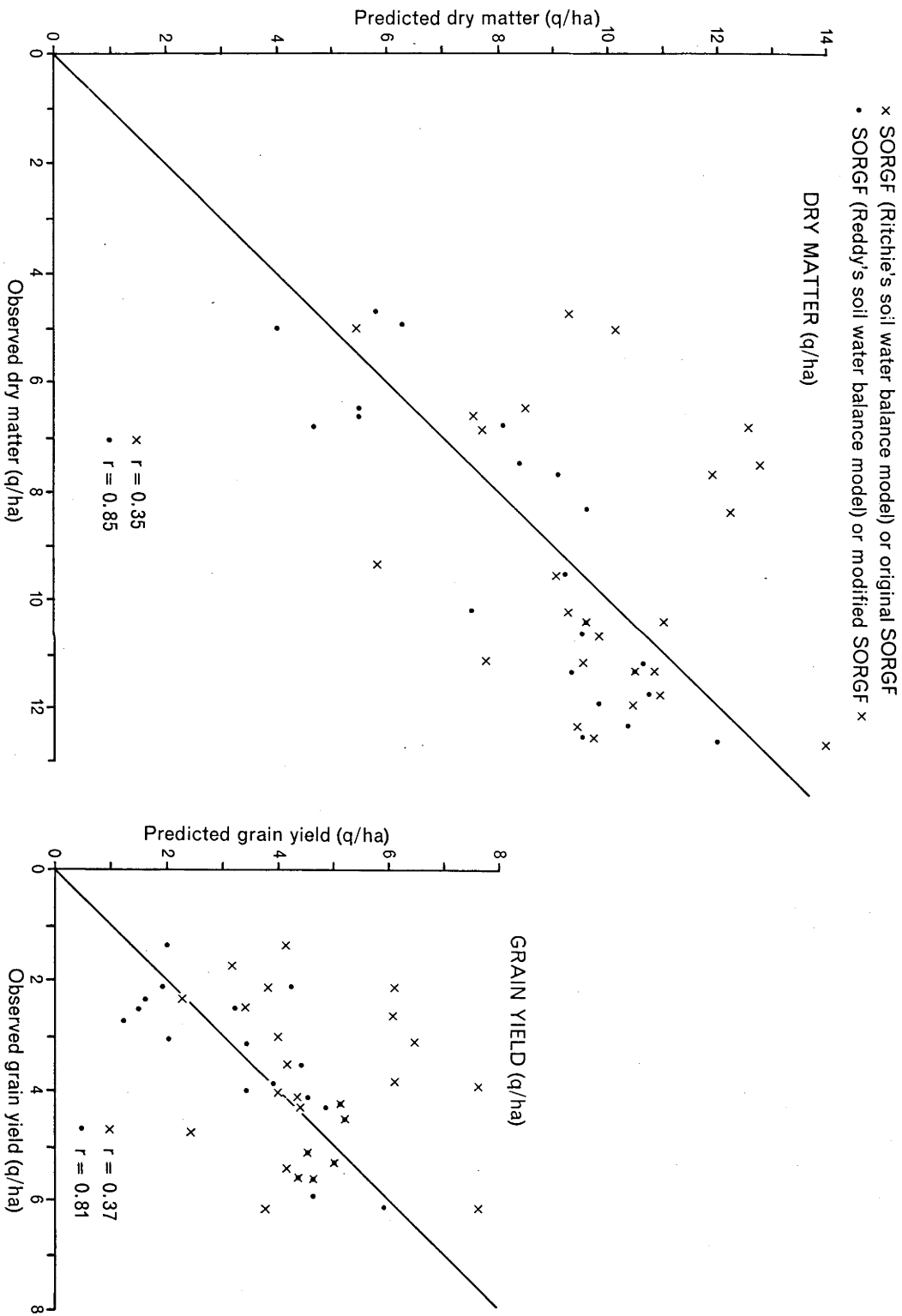


Figure 5-1 : Comparison of observed and predicted dry matter and grain yields (years: 1979 and 1980; seasons: Kharif and Rabi; sorghum cultivars: CSH1, CSH6, CSH8, M-35-1 and SPV-351).

Indore in the dry-to-moist semi-arid zone. Weekly rainfall data are the same as those previously used (Chapter 4) and open pan evaporation estimates are obtained by the procedure of Reddy (1979a). The rainfall is assumed to have occurred on day 1 and to be zero on the remaining 6 days of the week, while open-pan evaporation (US Class 'A': mesh covered) is assumed to be the same on all 7 days of the week. Using this data set, weekly evapotranspiration estimates, as a function of open water evaporation, along with soil moisture and runoff  $[RO_n + D_n = (RO + D)_n]$ , are computed for each year. From these estimates, the AE/E at different probability levels are presented in Figs. 5-2 to 5-8. The probabilities for different values of AE/E (0.0, 0.1, 0.2 . . . . 0.9, 1.0) are estimated by a simple frequency estimates approach and then through graphical interpolation the AE/E values for different levels of probabilities are estimated. These figures also show the soil moisture  $(M_n)$  and runoff  $(RO+D)_n$  at the 50% probability level. Crop water requirements for a 100-day sorghum are estimated (Reddy, 1983b) using the yield prediction models of Jensen (1968), Hiler & Clark (1971), and Minhas et al. (1974), and the results of Hiler et al. (1974). These are shown as histograms in the same figures. For an unlimited-water response by sorghum, AE/E values should exceed the crop water requirement for the duration of the crop. Finally, some of these results are used to compare with agroclimatic variables.

In formulating the agronomic relevance of the agroclimatic variables, these variables are compared with crop performance data of a few selected locations from India.

### 5.3 SOIL-WATER BALANCE SIMULATION RESULTS [INDIA]

Jodhpur: Figure 5-2 presents soil-water balance simulation results for Jodhpur; under alfisols with  $K^1 = 100$  mm, for a 100-day crop sown on week 28. The AE/E pattern is above the 75-day crop water requirement histogram (adjusted from the 100-day water requirement histogram proportion to 75-days) for only 30% of the years. By raising

---

<sup>1</sup>K = available water capacity in the root zone of the crop within 1.8 m depth of the soil; kharif = rainy season; rabi = post rainy season; 100/180 refer to intercropping of early maturing variety of 100 day and late maturing variety of 180 days [for example 100 day sorghum & 180 day pigeonpea]; 90+100 refer to double cropping of 90 day kharif crop followed by 100 day rabi crop [for example 90 day maize followed by 100 day chickpea]



this to 50%, it appears that the crop suffers, due to water stress, at different growth stages. The AE/E pattern is based on individual weekly probabilities only and hence they do not represent a continuous period in any one season. At 50% probability the soil moisture is nearly zero by the end of September. Therefore, at Jodhpur, a 75-day crop may only be feasible in 30% of the years.

**Anantapur:** Figure 5-3 presents soil-water balance simulation results for Anantapur; with  $K = 50, 100, 150$  and  $200$  mm for a 100-day crop sown on week 35. The 4 values of  $K$  represent shallow alfisols, moderately deep alfisols, deep alfisols or moderately deep vertisols and deep vertisols, respectively. Generally the runoff is high for alfisols, while it is considerably lower for vertisols. In the shallow alfisols, a 100-day crop is successful in only 30% of the years, while in deep vertisols it is successful in 50% of the years. Success can be substantially improved for alfisols as there is great potential for runoff recycling. The AE/E pattern suggests that in some years even longer duration crops can be grown (sown early in the season).

**Bangalore:** Figure 5-4 presents soil-water balance simulation results for Bangalore; with  $K = 100$  mm, for a 100-day crop sown on week 27. Generally, the runoff is not high during the initial stages of a crop sown on week 27, at which time the crop occasionally suffers due to water stress. The soil moisture reaches zero by about the end of August. However, the soil moisture gradually builds up later in the season. Therefore, a crop sown in the later part of the season is more successful than a crop sown early in the season. However, to take advantage of early rains (when soil moisture can reach 80% of the capacity in more than 50% of the years) and to reduce soil erosion it may be advantageous to grow a short duration crop early in the season (by about May), which can be harvested by late August. The 100-day crop sown on week 27 is successful in only 60% of the years, with the possibility of stress occurring in the reproductive stage (not a good practice).

**Hyderabad:** Figures 5-5a and b present soil-water balance simulation results for Hyderabad, with  $K = 100$  and  $200$  mm representing alfisols and vertisols respectively, for a 100-day crop sown on week 27. Generally, the soil moisture curves follow the pattern in Fig. 5-4, but in August the soil moisture is above 50% capacity. Runoff is also considerable during the early stages of crop growth in the alfisols. Table 5-1 presents the success

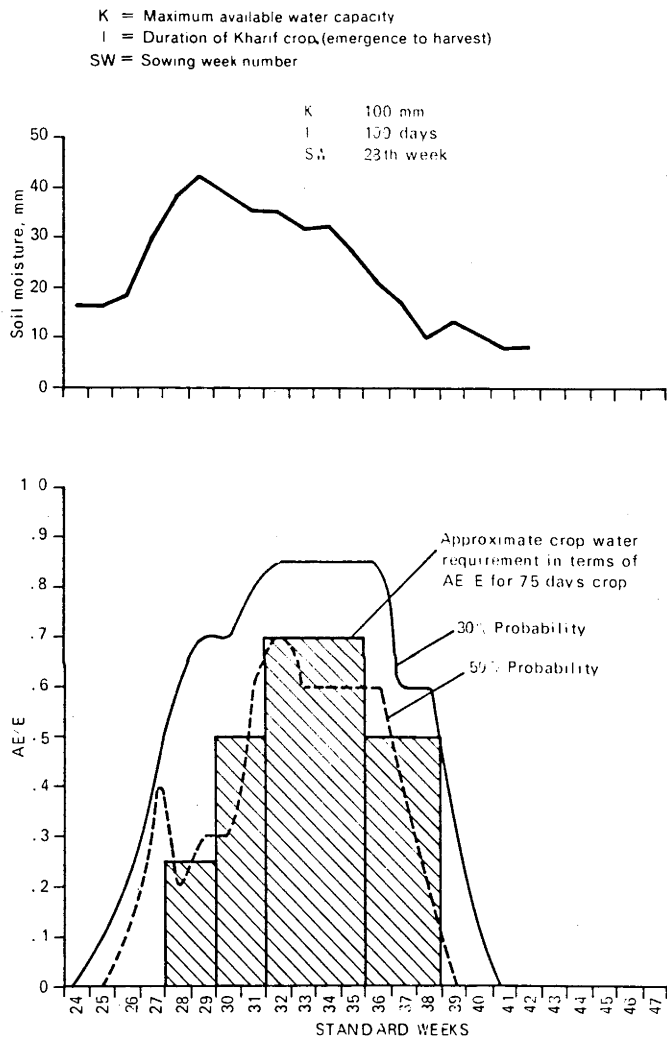


Figure 5-2 : Soil water balance results of Jodhpur.

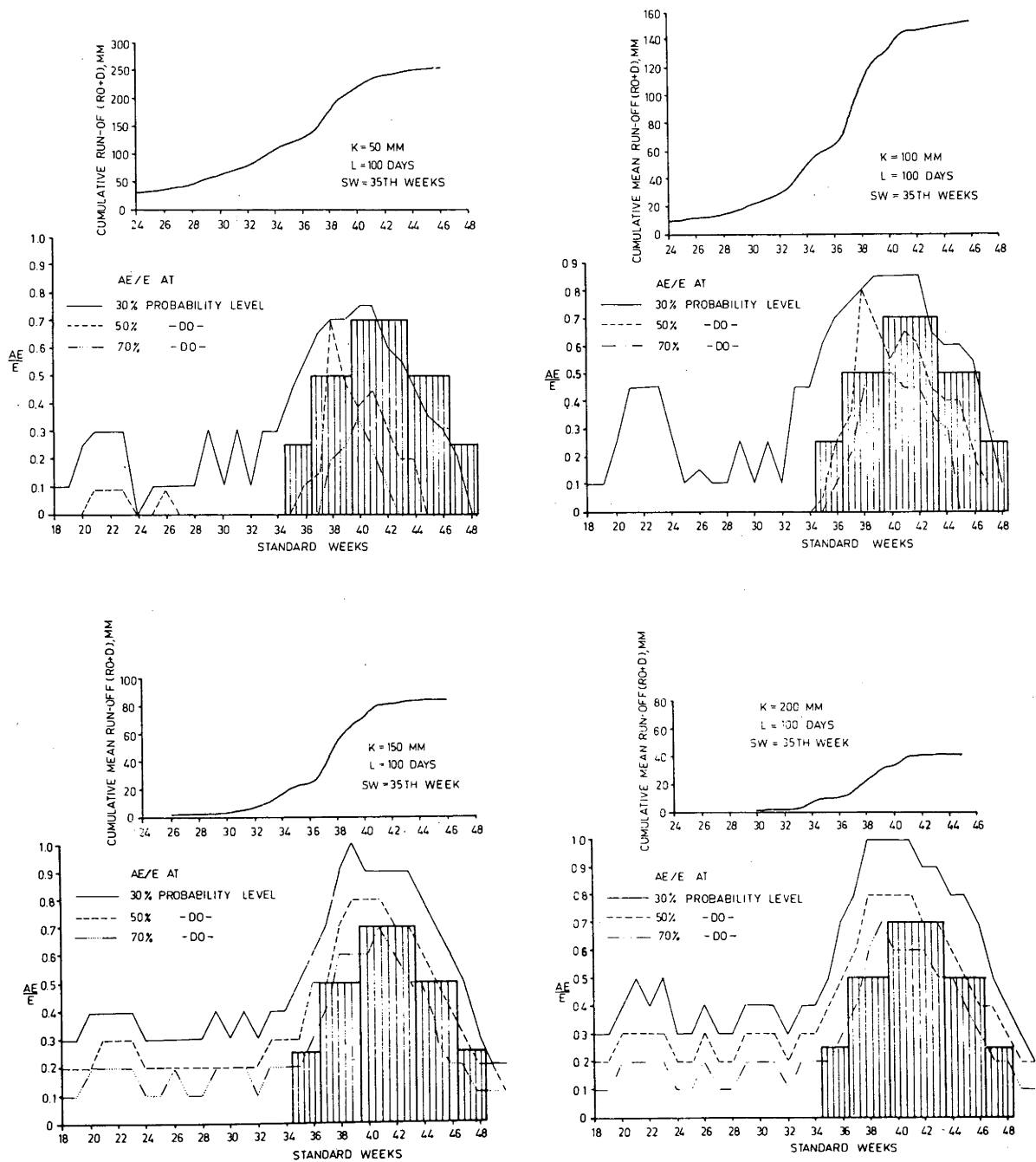


Figure 5-3 : Soil water balance results of Anantapur.

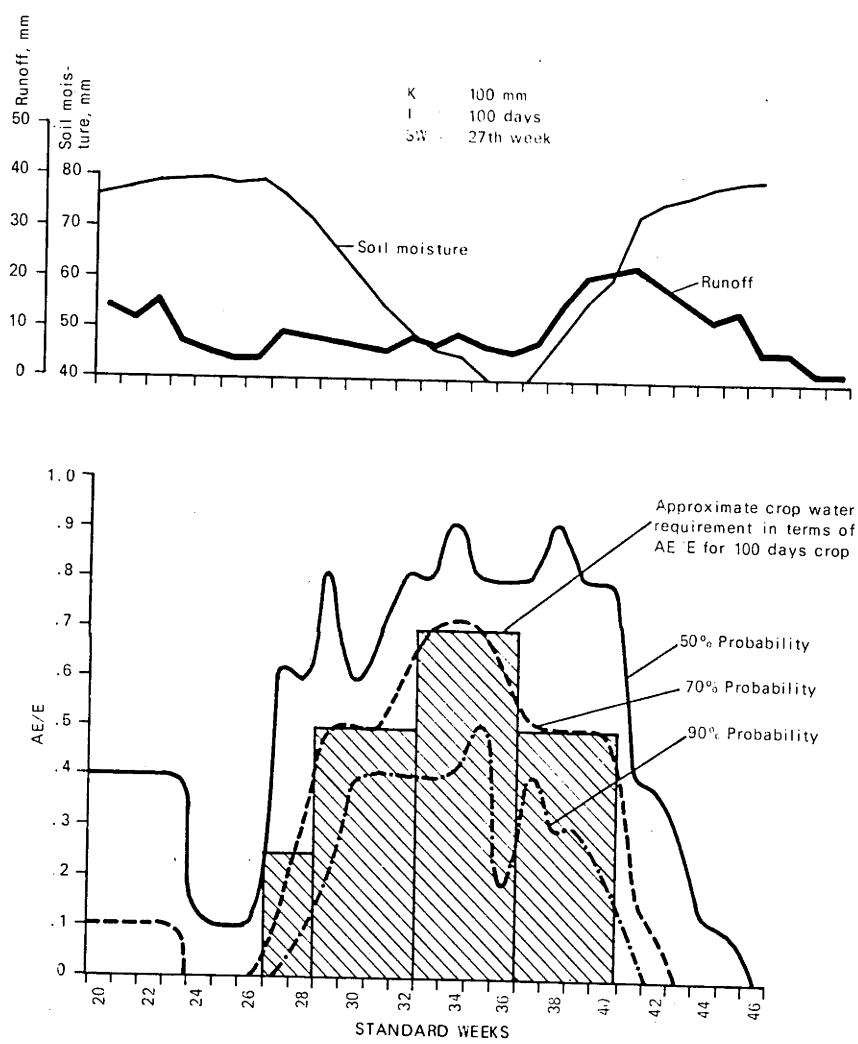


Figure 5-4 : Soil water balance results of Bangalore.

of different cropping patterns on a seasonal basis. In both alfisols and vertisols, a 91-day kharif crop is successful in 91% of the years. Following this, a 100-day rabi crop is successful in 56% of the years for vertisols and 27% of the years for alfisols. In 43% (vertisols) and 36% (alfisols) of the years there is a possibility of receiving rains more than 50 mm at harvest. For a 105-day kharif crop, success is the same as that of 91-day crop, but the success of a 100-day rabi crop is reduced substantially, to 13% (alfisols) and 36% (vertisols). An intercrop of 91/180 days is successful in 83% (alfisols) and 90% (vertisols) of the years. This is undoubtedly the best cropping pattern for the Hyderabad region for both alfisols and vertisols. However, with good, early rains, a sequential crop is also possible for vertisols. Runoff recycling appears to be economically viable for alfisols and this practice is also helpful in vertisols for germination of seeds in the rabi.

**Sholapur:** From Table 5-1, under deep vertisols ( $K = 200$  mm), a 70-day crop can be seen to be successful in 75% of the years with a risk of rains of more than 50 mm at harvest, in 17% of the years. Similarly, they change to 58% and 25% with a 91-day crop, and 58% and 11% with a 105-day crop. A 70- or 91-day kharif crop followed by a 100-day rabi crop is successful in 81% of the years. This is reduced to 67% for a 105-day kharif crop followed by a 100-day rabi crop. Therefore, of these three cropping patterns, the most successful is a 70-day kharif followed by a 100-day rabi crop. Intercropping of 91/180 days is also successful in 75% of the years. Some of these features can be clearly seen in Fig. 5-6. A crop sown in early July suffers from stress during the early growth stages of a kharif crop.

**Akola:** At Akola the risk of rains at harvest of a kharif crop is less than at Hyderabad (30%, Table 5-1). A 91-day or 105-day kharif crop is successful at Akola in 100% of the years in deep and medium deep vertisols (Table 5-1). A 100-day rabi crop is successful in 33% and 14% of the years in medium deep vertisols, followed by a 91- and 105-day kharif crop; while they are respectively 42% and 19% in deep vertisols. An intercrop of 91/180 days is successful in 81% (medium deep) and 83% (deep) vertisols. In the early stages of crop growth runoff is substantial and can be successfully utilized through recycling to increase the productivity in the rabi (Fig. 5-7).

**Indore:** It can be seen from Table 5-1 that on deep vertisols ( $K =$

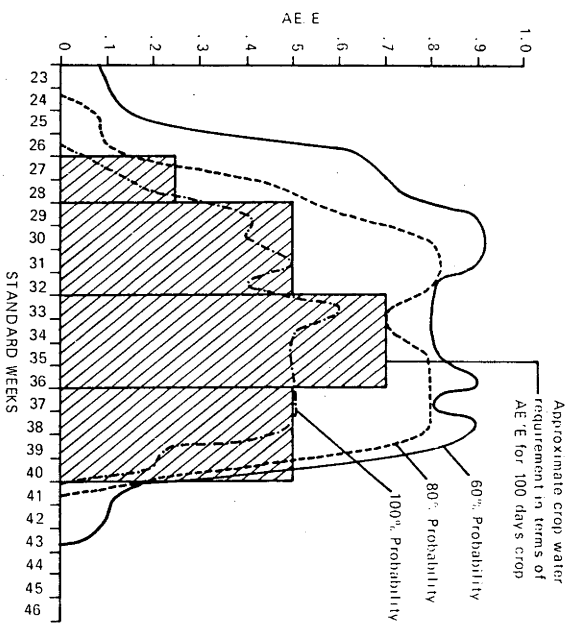
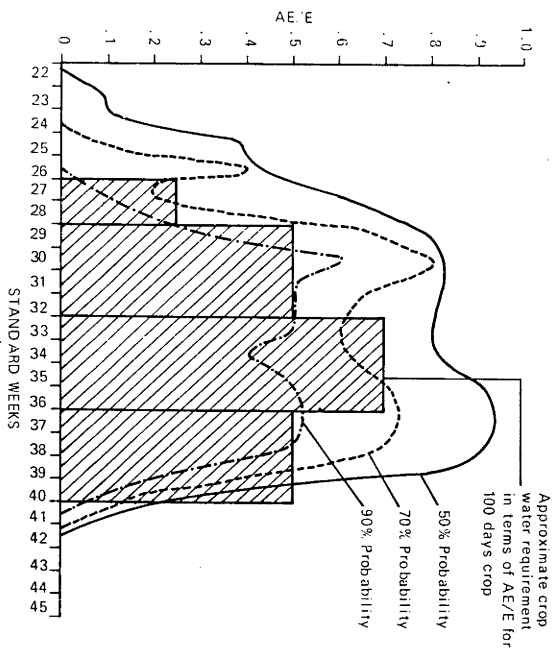
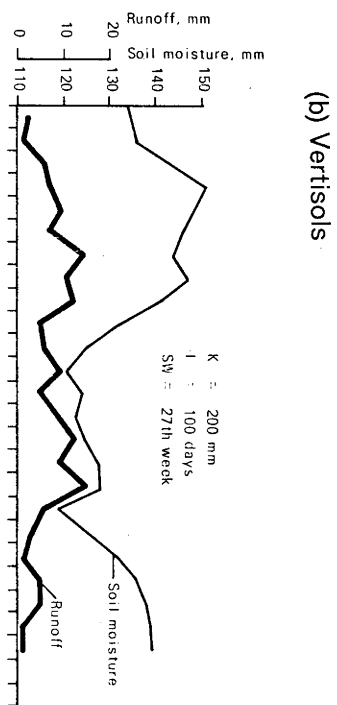
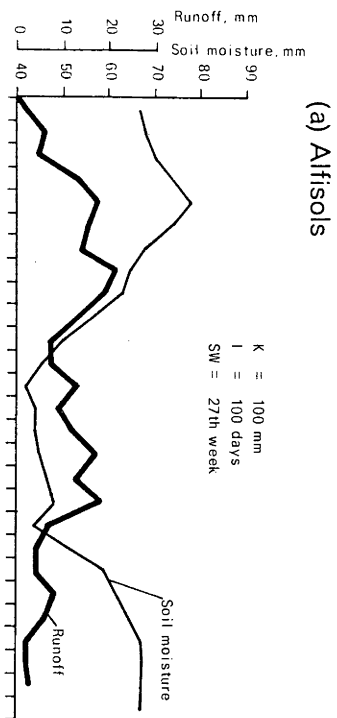


Figure 5-5 : Soil water balance results of Hyderabad.

Table 5-1 : Success of different crops in rainy and post-rainy seasons at few selected locations in India -- based on soil water balance simulation.<sup>a)</sup>

Crop duration (days)	Success*	Percentage success of different crops					
		Sholapur	Hyderabad		Akola		Indore**
		250	125	250	175	250	250
(----- K, mm -----)							
<u>Rainy season crop</u>							
70	a	75					
	b	17					
91	a	58	91	91	100	100	100
	b	25	36	43	22	28	62
105	a	58	91	91	100	100	100
	b	11	17	41	19	14	43
119	a		80	90	94	97	100
	b		4	30	0	3	0
<u>Intercropping</u> \$							
91/180		75	83	90	81	83	97
<u>Double Cropping</u> \$\$							
70+100		81					
91+100		81	27	56	33	42	81
105+100		67	13	36	14	19	51

\* a: Percentage success of Kharif crop, % years.

b: Rains more than 50 mm at harvest maturity; % years.

\*\* 40% of years problem of inter culturing

<sup>\$</sup> 91/180 refer to early maturing variety of 91 day and late maturing variety of 180 days (for example 91 day sorghum & 180 day pigeonpea).

<sup>\$\$</sup> 70+100 refer to 70 day rainy season crop followed by 100 day postrainy season crop (for example 70 day cowpea followed by 100 day sorghum).

a) After Reddy et al. (1982).

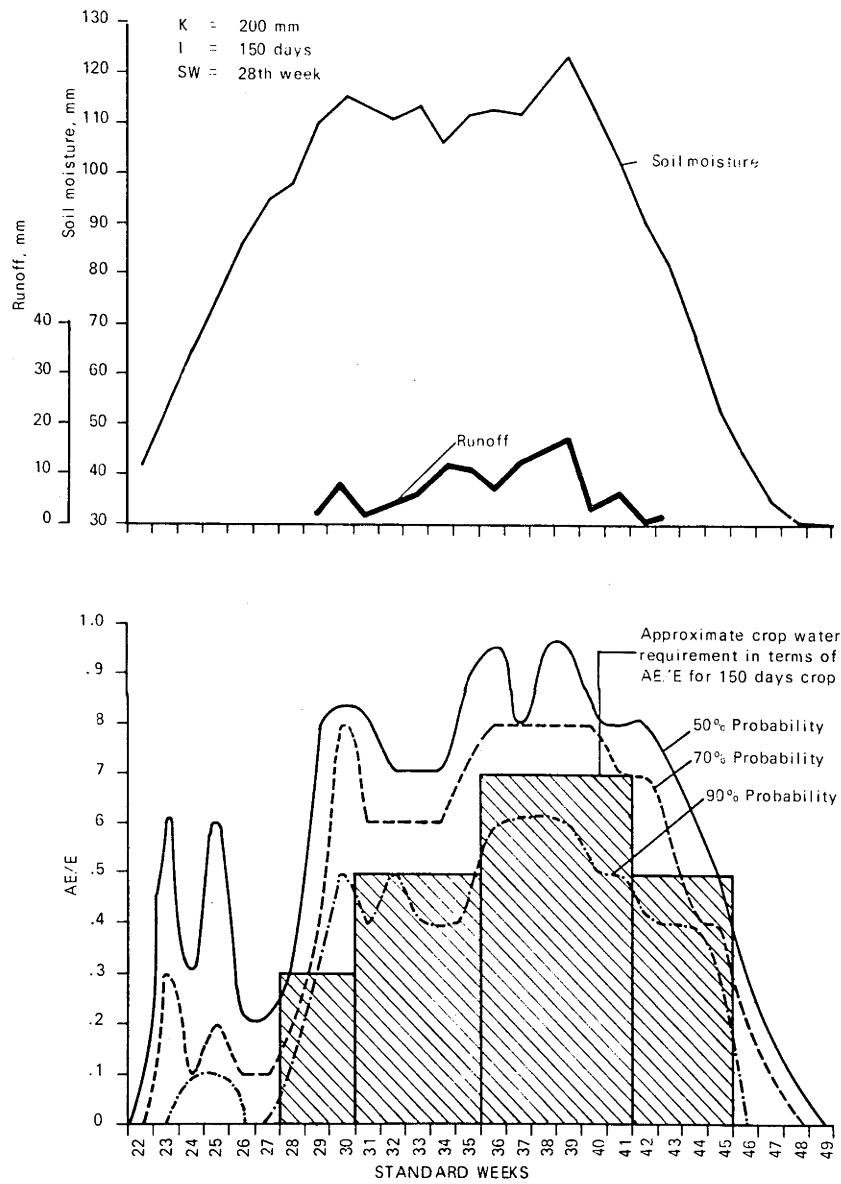


Figure 5-6 : Soil water balance results of Sholapur.



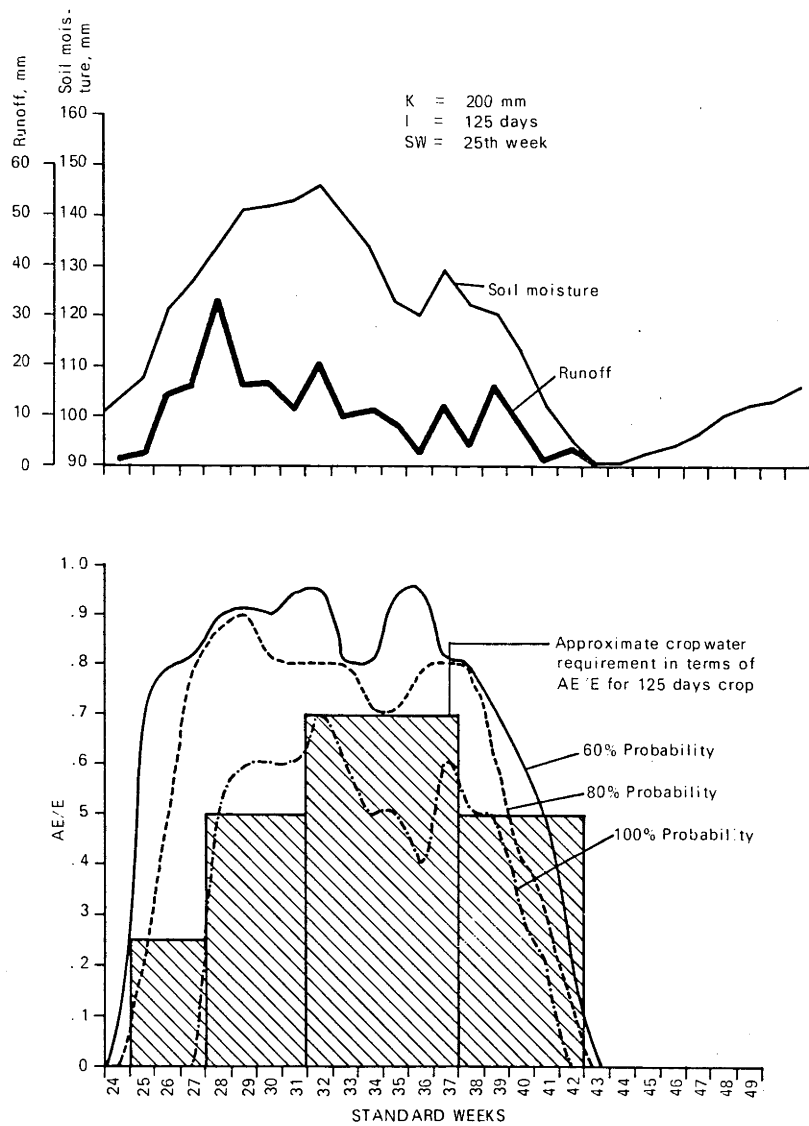


Figure 5-7 : Soil water balance results of Akola.

200 mm) at Indore the success of 91-, 105- or 119-day kharif crops is 100%. However, in 40% of the years, sufficient time may not be available for intercultural operations. Also, in 62%, 43% or 0% of the years, rains equal to more than 50 mm may occur at harvest of a 91-, 105- or 119-day kharif crop. Accordingly, a 119-day kharif crop would appear to be the best suited. However, the rabi crop success results suggest the opposite, as the success of a 100-day rabi crop is 81% after a 91-day kharif, reducing to 51% after a 105-day kharif crop. An intercrop of 91/180 days is successful in 97% of the years. It can be seen from Fig. 5-8 that runoff during the kharif crop growing season is substantial, which may cause serious water-logging problems.

#### 5.4 COMPARATIVE STUDY

In this section attempts are made to compare the soil-water balance results presented above with the agroclimatic variables and crop performance data in order to characterize those agroclimatic variables that relate to the crop and cropping pattern. Crop information is based on: (1) individual year's production figures accumulated as a result of the All India Coordinated Project for Dry-land Agriculture reports; and (2) synthesised results of ICAR (1982) and Spratt & Choudhury (1978). The data are in the form of means averaged over 3-7 years of the record (Table 5-2). There are insufficient data to attempt a year-to-year analysis.

In order to synthesise the results, the productivity data are discussed in relation to soil type. Each of the 20 research stations are assigned to at least one soil grouping. To obtain better appreciation of the results, arid and sub-humid locations are also used along with semi-arid locations.

##### 5.4.1 Aridisols

Jodhpur, Hissar and Anand are located on Aridisols. The first two are in the arid zone, while the third is in the semi-arid zone. Data for the important crops, together with the percentage area and farm yields, have been presented by Spratt & Choudhury (1978) for all 20 research stations and are also used in the present discussion. Jodhpur and Hissar have similar soil types and are more suitable for short duration crop varieties, like blackgram, guar, rape or mustard (60-75 days), with very low yields. At Anand, a long-duration cotton crop is grown in addition to

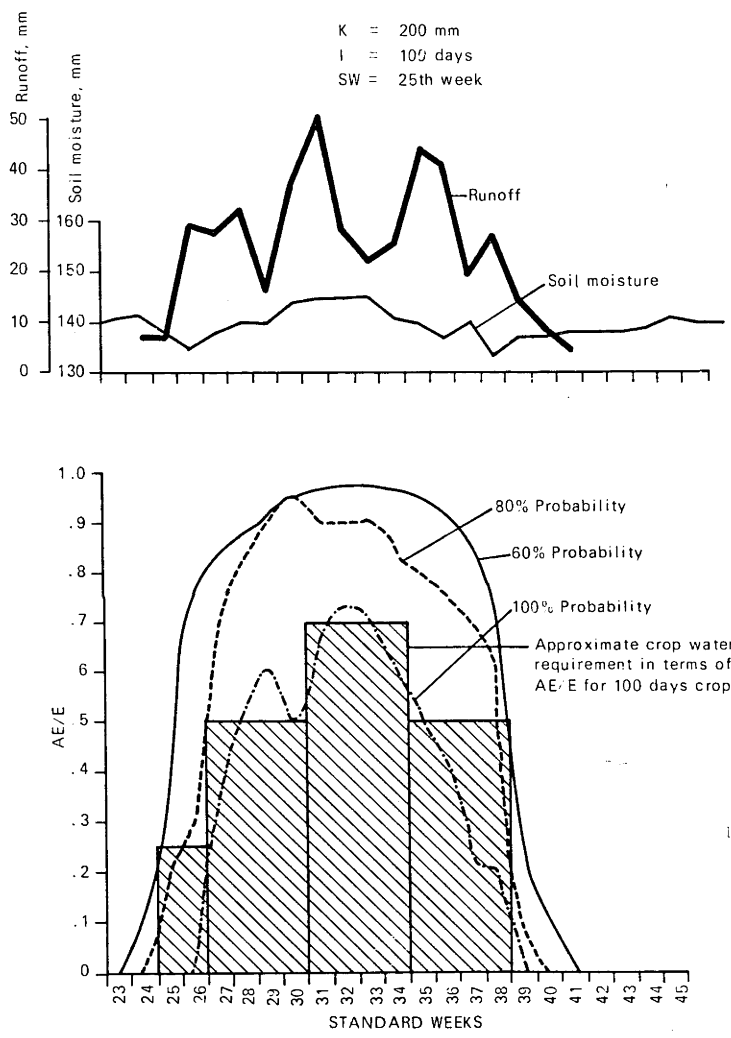


Figure 5-8 : Soil water balance results of Indore.

Table 5-2 : Cropping pattern performance results at (a) Anantapur, (b) Sholapur, (c) Akola, (d) Indore and (e) Dholi in India .

(a) Anantapur:

Grain yields, kg/ha				
Sole cropping			Intercropping	
Crop	Mean	s.d	Crops	Mean/mean
(based on 5-7 years data)			(based on 3 years data)	
		c.v.		
pearl millet	500 $\pm$ 290	58	pearl millet/pigeonpea	270/370
sorghum	980 $\pm$ 550	56	pearl millet/castor	210/260
groundnut	1080 $\pm$ 700	65	groundnut/pigeonpea	250/330
pigeonpea	550 $\pm$ 260	47	groundnut/castor	300/410
castor	850 $\pm$ 420	49		

(b) Sholapur:

Cropping pattern*		Grain yields, kg/ha				
Year:	1974-75	1975-76	1976-77	1977-78	1978-79	
PM/SF	695/ 443	1607/-	998/ 225	120/fail	1606/ 456	
PM/HS	1490/ 684	2095/-	1690/ 106	141/ 247	2316/ 431	
PM/PP	1504/1652	1892/2008	84/1438	535/ 85	555/2465	
GN/PP	-	1405/ 405	153/ 429	142/ 182	523/ 421	
SR/PP	-	1148/ 263	135/1019	33/ 225	181/2108	

\* PM = pearl millet; SF = safflower; HS = horsegram; GN = groundnut;  
PP = pigeonpea; SR = sorghum

## (c) Akola:

Crop	Grain yields, kg/ha					
	1971-72	1972-73	1973-74	1974-75	1975-76	1976-77
Pearl millet	710	860	1250	1200	-	-
Groundnut	520	1490	1500	1360	1490	-
Sorghum	1030	2080	2760	2270	-	2240
Sorghum/pigeonpea	-	-	-	-	2500/1300	-
Sorghum/safflower	-	-	-	-	4630/1410	2490/1400
Sorghum/chickpea	-	-	-	-	4690/ 340	2290/ 250

## (d) Indore:

Crop	Grain yields, kg/ha			
	1972-73	1973-74	1974-75	1976-77
Sorghum	3950	2760	2250	-
Maize	3520	2870	6100	-
Maize+chickpea	-	-	-	3970+1540
Sorghum+safflower	-	-	-	3680+1500
Soyabean+chickpea	-	-	-	2800+1480

(e) Dholi:

Grain yields, kg/ha						
Crop sequence	1976-77		1977-78		1978-79	
	# K	# R	K	R	K	R
Maize+wheat	3000	2810	3750	3640	2670	800
Maize+barley	3000	2590	3750	3640	2670	1830
Maize+peas	3000	2650	3750	2250	2670	1980
Maize+gram	3000	900	3750	2030	2670	930
Maize+mustard	3000	1360	3750	1530	2670	600
Maize+pigeonpea	3000	3260	3750	4220	2670	2800

# K = Kharif & R = Rabi

\* Pigeonpea as a rabi crop in India, by R.P. Roy Sharma, H.C. Thakur and H.M. Sharma, in Proc. Workshop on pigeonspeas, Vol. I, pp.26-36, ICRISAT, Patancheru, India, 1980.

pearl millet. It can be seen from Fig. 5-2 that at Jodhpur a 75-day (or 11-week) crop sown in July (week 28) is only successful in one out of three years, even with 100 mm available soil-water capacity. The crop suffers stress during different stages if the 30%-50% probability is considered. In addition, AE/E does not represent a continuous period for that season. By October the soil moisture reaches zero. These observations are also evident from the agroclimatic variables ( $S \pm \delta =$  week  $28.0 \pm 2.1$  weeks;  $G \pm \theta = 2.6 \pm 4.4$  weeks with  $A = 73\%$ ). The agroclimatic variables are also similar at Hissar except that  $\delta$  is high (5.9 weeks). The high  $\delta$  suggests that in the years of early rains, a short duration pearl millet can be grown. For Hissar, the recommended crops are grasses for grazing (*Eruca Sativa*, 1610 kg/ha) in place of rabi wheat (320 kg/ha) [ICAR, 1982]. At Anand, with  $S \pm \delta =$  week  $25.1 \pm 1.7$  weeks,  $G \pm \theta = 14.0 \pm 3.6$  weeks with  $A = 3\%$ , the variables suggest suitability for inter- or double cropping.

#### 5.4.2 Alfisols

Six stations are located on alfisols, namely Anantapur, Bangalore, Hyderabad, Jhansi (situated between Indore and Lucknow with  $G > 15$  weeks and  $S =$  week 25, with  $\theta = 3.0$  weeks and  $\delta = 1.5$  weeks), Ranchi and Bhubaneswar (situated near Phulbani with  $G \pm \theta = 21.5 \pm 3.9$  weeks and  $S \pm \delta =$  week  $22.7 \pm 3.0$  weeks). The first four are in the semi-arid tropics while the last two are in the sub-humid zone.

Anantapur and Bangalore have similar soil types and appear to be more suitable for single cropping, but better yields are obtained at Bangalore than at Anantapur. Table 5-2 shows that, considering their stability (low coefficient of variation(c.v.)), pigeonpea and castor are best suited, but in terms of yields, groundnut followed by sorghum, castor, pigeonpea and pearl millet are more productive at Anantapur. The intercrop yields are generally low. At Anantapur the following cropping patterns appear to be the most profitable.

<u>Good rains in:</u>	<u>Crop</u>
July	Castor (150-day)
the 1st fortnight-August	Groundnut(120-130-day)
the 2nd fortnight-August	Pearl millet(90-110-day)
early September	Pearl millet(75-90-day)
late September	Horsegram(60-75-day)

This pattern is also indicated by the agroclimatic variables  $S$  and  $G$ , high variability in the onset times of sowing rains and the effective rainy

period ( $S \pm s = \text{week } 35.5 \pm 4.8 \text{ weeks}$  and  $G \pm e = 5.2 \pm 5.4 \text{ weeks}$ ), by the soil-water balance results (AE/E pattern, Fig. 5-3), and similar results are obtained from agroclimatic variable A (52%), which suggest that a 75-day crop is successful in 40%-50% of the years in alfisols ( $K = 50$  and  $100 \text{ mm}$ ). There is a high probability of obtaining sufficient runoff during the initial stage of crop growth and, therefore, of runoff recycling to increase productivity.

At Bangalore, a 100-day crop is successful in 70% of the years on alfisols ( $K = 100 \text{ mm}$ ). However, there is a possibility of drought in late August with soil moisture reaching as low as zero in more than 50% of the years (Fig. 5-4). Sufficient runoff occurs in late September to suggest that it can be utilized for the rabi crop (during its later stages). At Bangalore, finger millet is therefore generally planted in August after soil-water storage has built up sufficiently to overcome drought. However, this is not a good practice as, according to the AE/E pattern for May to August shown in Fig. 5-4, there is scope for growing a short duration (60-75-day) pulse-crop after very good early rains. According to ICAR (1982), cowpea followed by finger millet ( $670 + 1530 \text{ kg/ha}$ ) and a groundnut/pigeonpea intercrop ( $1440/570 \text{ kg/ha}$ ) also give better yields. This practice not only reduces soil erosion but gives monetary returns as high as finger millet sown in August. Consequently, the following practices are recommended at Bangalore:

- with early rains - cowpea (May - August) + finger millet (August - October), sequence cropping;
- with mid-July rains - groundnut/pigeonpea (120/180 days), intercropping;
- with August rains - finger millet (110 days), single cropping.

Pearl millet has been found unsuitable for the Bangalore region, as frequent rains during the early kharif result in pollen wash; late sowing suffers from ergot disease, and sorghum seeds are blackened due to rain at maturity<sup>2</sup>.

Agroclimate variables confirm the validity of some of these features. The mean week of sowing rains and its s.d ( $\text{week } 26.4 \pm 4.7 \text{ weeks}$ )

---

<sup>2</sup>from research (1971-1976) at University of Agricultural Sciences, Hebbol Campus, Bangalore



suggest that good rains are possible as early as May in some years but may be delayed to as late as August, with an effective rainy period of only  $11.8 \pm 8.4$  weeks. The large value of  $\theta$  (8.4 weeks) is mainly associated with the August drought observed in Fig. 5-4.

At Hyderabad, unlike Bangalore, there is a good possibility of using runoff during the initial stages of crop growth (Fig. 5-5a), but here also the soil moisture level decreases to as low as 50% in 50% of the years during late August and early September. A 100-day crop is successful in ~70% of the years. July sowing appears to be better than June sowing in alfisols, while in vertisols June sowings are better (Fig. 5-5b). Sorghum planted in early July gave 1720 kg/ha, while the late-planted (early August) crop gave very low yields of 80 kg/ha (ICAR, 1982). Sorghum/pigeonpea intercropping (2710/800 kg/ha) and pearl millet + horsegram double crops (3010 + 1000 kg/ha) also gave good yields. These features are confirmed by the soil moisture reserve at the end of kharif crop harvesting in early October (Fig. 5-5a), and are also evident from the agroclimatic variables ( $S \pm s$  = week  $27.2 \pm 2.9$  weeks and  $G \pm \theta$  =  $12.9 \pm 5.8$  weeks with  $A = 13\%$ ). Double cropping is therefore successful with good, early sowing rains, and with late sowing rains intercropping is preferable. On soils with low water holding capacity ( $K = 50$  mm) only pearl millet can be grown as a single crop; with  $K = 100$  mm, either pearl millet/castor intercrop or pearl millet + horsegram sequence cropping are possible; and with under  $K = 200$  mm either a sorghum/pigeonpea intercropping or sorghum + chickpea sequence cropping [FSRP(ICRISAT) Annual Reports, 1974-1981, Binswanger et al. (1980)] is successful.

At the other three locations, Jhansi, Ranchi and Bhubaneswar, double crops are successful, although at Jhansi cropping could be based on maize or finger millet, while at the other two locations paddy-rice or finger millet based double cropping is successful in vertisols or alfisols. This type of cropping pattern is also evident from the agroclimatic variables. At Ranchi, with  $S \pm s$  = week  $23.9 \pm 2.9$  weeks,  $G \pm \theta$  =  $16.4 \pm 3.8$  weeks,  $W \pm \alpha$  =  $7.5 \pm 3.4$  weeks and  $D \pm \beta$  =  $3.7 \pm 1.8$  weeks, paddy-rice + barley (or linseed) and maize + barley (or linseed) sequence cropping gave high yields in 1972-73 and 1973-74; with maize and paddy-rice having nearly equal yields (Spratt & Choudhury, 1978; ICAR, 1982). In terms of local preference, paddy-rice is important.

However, if the sowing of paddy-rice is delayed beyond the second week of July, the yields are reduced substantially (from 2000 kg/ha in early July to 800 kg/ha in late July: ICAR, 1982). The maize/pigeonpea intercrop (3370/680 kg/ha) yields are not good compared with those of paddy-rice + linseed (3800 + 1500 kg/ha). It can also be seen from the results for Dholi, in Bihar (near to Patan with  $S \pm s = \text{week } 24.1 \pm 2.5$  weeks and  $G \pm e = 18.5 \pm 3.9$  weeks), that this region is suitable for double cropping (Table 5-2).

According to Mohsin & Sinha (1979), double cropping based on finger millet is successful on alfisols. On vertisols, double cropping based on paddy-rice is successful with early sowing rains, and on maize with late sowing rains. The situation is similar at Bhubaneswar and Jhansi, but water-logging problems are severe at Ranchi and Bhubaneswar as long wet spells occur. Because of this problem paddy-rice or maize is more suitable than sorghum for these regions while maize or sorghum is more suitable at Jhansi, where wet spells are shorter. Mohsin & Sinha (1979) suggested that runoff, which is very likely to occur, should be collected and used to increase the productivity of the rabi.

#### 5.4.3 Alluvial soils (entisols)

Two stations are located on entisols, namely Agra and Varanasi. At Varanasi, yields from pearl millet + chickpea double cropping are superior to any other pearl millet-based double cropping (Spratt & Choudhury, 1978). However, upland rice yields are superior to pearl millet, and maize yields and chickpea are superior to pigeonpea, wheat, blackgram, greengram, and barley. Therefore, paddy-rice based (paddy-rice + chickpea) double cropping is successful at Varanasi and pearl millet/pigeonpea intercrop or pearl millet + chickpea sequence cropping is successful at Agra. These combinations are also indicated by the agroclimatic variables, with a high stability for the cropping pattern ( $S \pm s = \text{week } 26.3 \pm 1.0$  week at Agra and  $\text{week } 25.1 \pm 1.4$  weeks at Varanasi;  $G \pm e = 13.3 \pm 3.6$  weeks at Agra and  $16.5 \pm 3.5$  weeks at Varanasi). Water-logging problems are also more severe at Varanasi ( $W \pm \alpha = 7.0 \pm 2.1$  weeks and  $D \pm \beta = 5.3 \pm 2.0$  weeks) compared to Agra ( $5.9 \pm 2.0$  and  $5.1 \pm 1.9$  weeks, respectively). Double cropping based on paddy-rice is, therefore, more suitable at Varanasi, while double cropping based on sorghum or pearl millet is more suitable at Agra.

#### 5.4.4 Vertisols

Nine stations are located on vertisols, namely Bellary, Bijapur, Sholapur, Rajkot, Udaipur, Kovilpatti, Akola, Indore and Rewa. Except Rewa, which is in the sub-humid zone, all locations are in the semi-arid tropics.

Bellary, which is similar to Anantapur but has different soils, is more suitable for sorghum (2670 kg/ha) than the traditional long duration cotton (200 kg/ha), because of the short, highly variable growing season ( $\delta = 3.7$  weeks and  $\theta = 5.9$  weeks). It is also evident from Fig. 5-3 that a 100-day crop is successful in only one out of two years in deep vertisols ( $K = 200$  mm). In this situation the possibility of runoff is low, and it is better to store water in the soil by fallowing and to take a rabi crop of 90 to 100-day sorghum.

At Bijapur, sowing rains commence rather early compared with Bellary. The mean week for commencement of sowing rains is week  $32.3 \pm 3.7$  weeks and the growing season is  $6.0 \pm 6.4$  weeks. Among several cropping patterns<sup>3</sup>, rabi sorghum appears to be most suitable and gives high yields (2035 kg/ha, average for three years). Next in order is safflower and groundnut/pigeonpea intercrop (723/1161 kg/ha). If good sowing rains are early, groundnut/pigeonpea intercropping is the best, but if these rains are late, only rabi sorghum is possible. Supplementary irrigation was also found to be beneficial to the rabi crop. However, on vertisols, Dharwar ( $S \pm \delta = 28.6 \pm 3.6$  weeks and  $G \pm \theta = 9.0 \pm 7.3$  weeks) appears to be more suitable for a short duration pulse-crop, followed by a cereal rabi crop with early sowing rains or only rabi sorghum with late rains (these are based on soil-water balance simulation results presented by Reddy et al., 1977). The situation is similar to Bangalore (Fig. 5-4).

At Sholapur, like Bangalore, the agroclimatic variables show high variability ( $S \pm \delta = 27.7 \pm 4.0$  weeks and  $G \pm \theta = 11.3 \pm 6.4$  weeks). Figure 5-6 shows that ~75% of the years, intercropping is successful in deep vertisols ( $K = 200$  mm), while a short duration kharif crop followed by a rabi crop is successful in 75% and 81% of the years, respectively. If the duration of the kharif crop exceeds 75 days then the success of the

---

<sup>3</sup>Dry farming Research in black soils of Bijapur [Karnataka] 1971-80. University of Agricultural Science, Agricultural Research Station, Bijapur

kharif crop reduces from 75% to 58% (Table 5-1, Reddy et al., 1982). Consequently, the Sholapur region is suitable for double cropping with good early rains or intercropping if these rains are late. The yield data also indicate this suitability (Table 5-2), where a 90-day pearl millet crop experiences considerable long-term variation and pigeonpea with pearl millet performs better. The kharif fallowed rabi yields also gave better results (ICAR, 1982). For the Sholapur region, therefore, the following cropping patterns are better suited:

- In late June with good sowing rains - cowpea followed by sorghum sequence cropping;
- in early July with good sowing rains - pearl millet/pigeonpea intercropping;
- in late July-August good sowing rains - sorghum, single cropping.

In the same situation at Hyderabad, with slightly more stable rains in many years, double crops are successful and intercropping is even better (Fig. 5-5b, Table 5-1). Research station results at the ICRISAT Centre (Binswanger et al., 1980) also suggest this. A sorghum kharif crop, or even maize in some years, is successful but occasional water-logging and harvesting problems are possible with these crops. Rajkot, with a slightly shorter growing season ( $S \pm s = \text{week } 26.2 \pm 3.0 \text{ weeks}$  and  $G \pm e = 9.6 \pm 5.3 \text{ weeks}$ ), is not suitable for double cropping but is highly suitable for intercropping. Better yields are obtained with pearl millet, blackgram, groundnut and pigeonpea (ICAR, 1982). Either groundnut/pigeonpea or pearl millet/pigeonpea intercropping may, therefore, be better cropping systems for the vertisol regions of Rajkot. At Udaipur, with a slightly longer growing season than Hyderabad ( $S \pm s = \text{week } 25.7 \pm 2.4 \text{ weeks}$  and  $G \pm e = 14.1 \pm 3.7 \text{ weeks}$ ), double crops perform better. For example, sorghum yielded  $1545 + 1205 \text{ kg/ha}$  and maize yielded  $1545 + 1406 \text{ kg/ha}^4$ , suggesting that sorghum is better than maize in the Udaipur region. Urd + Chickpea double crops ( $1016 + 1830 \text{ kg/ha}$ ) followed by sorghum/pigeonpea intercrop ( $3142/613 \text{ kg/ha}$ ) and maize + chickpea sequence cropping are also suitable ( $374 + 1894$

---

<sup>4</sup>based on four from five years research [1971-1976] at Rajasthan College of Agriculture, University of Udaipur, Udaipur

kg/ha; ICAR, 1982). Therefore, with early sowing rains, sorghum or maize-based double cropping, or with late sowing rains, a sorghum or maize/pigeonpea intercrop is highly successful. At Kovilpatti (near Madhurai, with  $S \pm s = \text{week } 34.0 \pm 5.3$  weeks and  $G \pm e = 12.6 \pm 6.7$  weeks), sorghum planted before the traditional planting date (week 44) performed well (2510 kg/ha). The recommended practice is (ICAR, 1982) single cropping of sorghum, pearl millet or cotton in October, or safflower in November. This means that at Kovilpatti, with good early sowing rains, intercropping with sorghum or pearl millet should be adopted and, with late rains only, single cropping of sorghum, pearl millet or safflower is the better system.

At Akola ( $S \pm s = \text{week } 25.0 \pm 1.9$  weeks and  $G \pm e = 14.0 \pm 3.6$  weeks), a 100-day crop is successful in 90% of the years (Fig. 5-7). In some years there is a possibility of drought occurring in late August. In the beginning of the kharif crop growing season there is a good possibility of obtaining high runoff and this can be used to increase the yields of rabi crops. There is also a strong possibility of water-logging problems occurring. The yield data suggest that sorghum is a more stable crop, compared with pearl millet in the Akola region. A sorghum + safflower sequence cropping pattern is also better than others (Table 5-2). Consequently, the recommended practice in the Akola region is that in deep vertisols, sorghum + safflower sequence cropping should be adopted, and in shallow soils, a pearl millet/pigeonpea intercropping is best suited.

At Indore ( $S \pm s = \text{week } 24.7 \pm 1.3$  weeks and  $G \pm e = 16.9 \pm 3.1$  weeks), a 100-day crop is successful in 100% of the years, with soil moisture above 50% capacity throughout the kharif growing season and there is a possibility of high runoff (Fig. 5-8), consequently, there are severe water-logging problems. Most areas in this region are kept fallow during the rainy season. In general, double crops based on maize perform better (Table 5-2). The appropriate cropping patterns in the Indore region are maize or paddy-rice based double cropping with early sowing rains, or maize or sorghum based double cropping with late sowing rains. According to ICAR (1982) paddy-rice performance is as good as any other crop (paddy-rice, 3240 kg/ha; maize, 3600 kg/ha).

Rewa ( $S \pm s = \text{week } 25.0 \pm 1.1$  weeks and  $G \pm e = 16.1 \pm 2.3$  weeks) is found to be more productive for double cropping based on paddy-rice. Paddy-rice + wheat double cropping yielded 2430 +1960

kg/ha. After paddy-rice (3730 kg/ha), the next in order is finger millet (2680 kg/ha), ICAR (1982). For rabi, after wheat (1860 kg/ha), chickpea (1750 kg/ha) and barley (1570 kg/ha) yields are good (ICAR, 1982). This region, like Ranchi, is suitable for paddy-rice-based double cropping in vertisols and finger millet-based double cropping in alfisols.

## 5.5 INTEGRATION OF AGROCLIMATIC VARIABLES WITH FARMING SYSTEMS

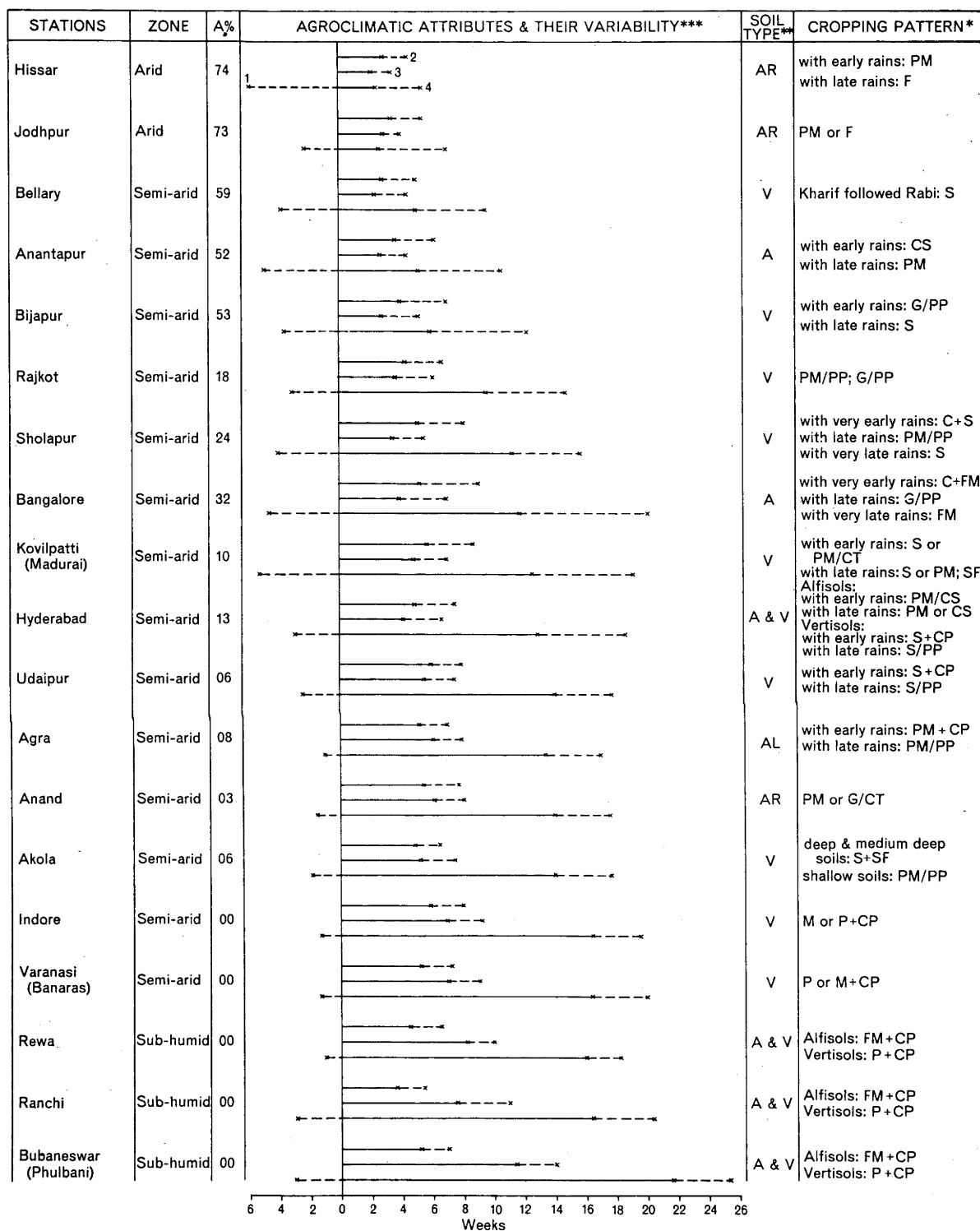
The results of this comparative analysis of agroclimatic variables and established cropping patterns in India are presented in tabular form (Fig. 5-9). In Fig. 5-9, the solid lines represent means and the dotted lines represent standard deviations. Clearly, the cropping pattern is not only influenced by the average available effective rainy period ( $G$ ), but also by its variability ( $C$ ), as well as the variability in the time at which the sowing rains commence ( $\delta$ ). Three locations, namely Bangalore, Sholapur and Hyderabad, with about the same available effective rainy period but having considerable differences in the level of dependability [defined by  $\delta$  and  $\sigma$ ], are compared as examples. Dependability is low [large  $\delta$  and  $\sigma$ ] at Bangalore while it is considerably higher at Hyderabad [low  $\delta$  and  $\sigma$ ]. Sholapur lies between these two situations, having nearly the same  $\sigma$  as that of Hyderabad, but  $\delta$  is greater than that at Hyderabad. In association with these parameters, the recommended cropping patterns on the two main soil types at these three locations are summarized below.

### Alfisols:

- Bangalore: With good early sowing rains, double crops should be grown, the kharif crop being of very short duration (~75-day). When these rains are very late, only a single 100-day crop should be grown.
- Hyderabad: With early sowing rains, double crops should be grown, the kharif crop being of medium duration (90 to 100-days), and when these rains are late a 90/150 days intercrop should be grown.

### Vertisols:

- Sholapur: With early sowing rains, double crops should be grown, the kharif crop being of very short duration (~75-day), and when these rains are late a single 100-day crop should be grown.



\* F = fodder; G = groundnut (130-180day); C = cowpea (60-75day); S = sorghum (90-100day); M = maize (90-100day); P = paddy (90-120day); PP = pigeonpea (150-180day); CP = chickpea (90-100day); CS = castor (130-150day); CT = cotton (130-180day); FM = finger millet (100-130day); SF = safflower (90-100day); PM = pearl millet (75-110day); S/PP eg. refers to sorghum and pigeonpea intercrop; and S+CP eg. refers to sorghum and chickpea double or sequential cropping

\*\* AR = Aridisols AL = Alluvial soils V = Vertisols A = Alfisols

\*\*\* 1 =  $\delta$  2 =  $\bar{D} + \alpha$  3 =  $\bar{W} + \beta$  4 =  $\bar{G} + \theta$

Figure 5-9 : Graphical presentation of agroclimatic variables together with recommended cropping patterns at selected locations in India.

- Hyderabad: With early sowing rains, double crops should be grown, the kharif crop being of medium duration (90 to 100-days), and when these rains are late a 90/180 days intercrop should be grown.

The crops that fit best into these cropping patterns differ significantly. They depend not only upon soil type but also on the length of wet and dry spells within the available effective rainy period. For example, the millet-based cropping pattern is best suited to alfisols and the sorghum-based cropping pattern to vertisols. In the vertisols at Hyderabad, where wet spells are shorter than dry spells, sorghum is the most suitable crop, while at Indore and Ranchi, where wet spells are longer than dry spells (wet spells being more than 5 weeks), maize and paddy-rice are better suited. At Ranchi, where wet spells are more than 7 weeks and the duration of dry spells is less than 70% of wet spells, paddy-rice is more suitable, while at Indore, where wet spells are less than or equal to 7 weeks and the duration of dry spells is more than 70% of wet spells, maize is more suitable. Similar conditions occur at Rewa and Banaras region, paddy-rice is cropped more frequently than at Indore.

Alfisols are characterized by low water holding capacities and hence, under highly variable rainfall, there is a good possibility of frequent water deficiencies during the effective rainy period. These soils are therefore more suitable for millets which are drought tolerant. Finger millet is more rewarding where wet spells last longer than 3 weeks, or wet spells are more frequent than dry spells (Bangalore, Rewa and Ranchi). Pearl millet is more suitable where wet spells do not exceed 3 weeks, or where wet spells are longer than 3 weeks but represent less than 70% of the duration of dry spells (Anantapur and Sholapur). However, wherever intercropping is practiced, pearl millet is more suitable than finger millet, as the former is less competitive with the long-duration crop (Hyderabad, Kovilpatti and Sholapur).

Vertisols are characterized by high water holding capacity and hence, with more frequent droughts, this soil type can maintain crops, such as sorghum, maize, paddy-rice, etc., which are less drought-tolerant than millets. As the proportion of wet spells increases, however, paddy-rice becomes more suitable than sorghum, as mentioned above.

Regions with short growing seasons and high variability in both onset and cessation times of sowing rains, are probably suitable either for



intercropping in the years of good early rains or a long duration single crop in those years with late rains. Single cropping is more suitable in alfisols (Anantapur, Bangalore, Sholapur and Kovilpatti) or, where left fallow in the rainy season, post-rainy season cropping is practiced in vertisols in regions where the available effective rainy period is less than 8 weeks (Bellary and Bijapur). Areas with long growing seasons are more suitable for double crops or intercropping. The locations with wet spells of more than 7 weeks and the dry spells having a duration of less than 70% of that for wet spells, appear to be more suitable for paddy-rice (early sowing rains). It appears, however, that delay in sowing reduces yields of paddy-rice substantially. Thus, with late rains, maize is more suitable in vertisols and finger millet in alfisols. These regions are less suitable for sorghum or pearl millet as the long available effective rainy period and the frequent heavy rains do not promote the growth of sorghum or pearl millet. They are also faced with severe water-logging problems and, therefore, are not suitable for dry-land agriculture in the rainy season. The regions with wet spells less than, or equal to, 7 weeks and wet spells longer than dry spells, are suitable for maize with early rains (paddy-rice is also suitable). The regions with more frequent wet spells than dry spells are more suitable for sorghum, pearl millet, groundnut, castor, pigeonpea or cotton, depending upon the available effective rainy period and the duration and frequency of the wet and dry spells. Temperatures are near optimum for the growth of many crops in the tropics, where the mean annual temperature is more than or equal to 18°C and remains at about this level during the rainy season (Reddy & Virmani, 1980b). Temperature is therefore not considered an important parameter in determining the suitability of rainy season crops. In the post-rainy season (rabi), however, temperature is important in determining which crops are suitable because the availability of soil water is often a limiting factor. These considerations are beyond the scope of this study; here, considerations are limited to whether or not the moisture level is sufficient to raise rabi crop. However, some of these inferences will certainly be modified by some of the soil and terrain constraints, particularly productive level.

## 5.6 SUMMARY

This chapter presents the characteristics of agroclimatic variables identified in the previous chapter as being relevant to farming systems. A soil-water balance simulation and agronomic data for selected locations in India were used to assist in this analysis. Based on these observations the successful cropping systems and crops for similar soil types have also been discussed. Clearly, the cropping pattern is not only influenced by the mean available effective rainy period but also by its variability, both commencement and termination. However, the crop varieties that are suitable for these cropping patterns differ significantly. They are associated more with soil type, and wet and dry spells within the available effective rainy period.

For example the following successful cropping systems, on similar soil types with different levels of dependability, are identified:

(1) With high variability in both the onset and cessation times of the rainy season [ $s$  and  $C$  are large] then:

- If the available effective rainy period is short ( $\leq 8$  weeks) and with early sowing rains, a long duration single crop or intercropping should be adopted, but if these rains are late then a single crop should be grown in alfisols, and in the vertisols a rabi single crop should be followed by a fallow kharif;
- if the available effective rainy period is moderately long (8–13 weeks), and with early sowing rains, intercropping should be adopted, but if these rains are late a single crop should be grown in alfisols, and in vertisols either double cropping (with early rains) or intercropping (with late rains) should be practiced;
- If the available effective rainy period is longer ( $> 13$  weeks), and with early sowing rains double crops should be grown, but with late rains intercropping should be practiced.

(2) Under more stable onset and cessation times for sowing rains [ $s$  and  $C$  are small] then:

- with a short available effective rainy period a single crop should be grown;
- with a moderate available effective rainy period, intercropping should be practiced in alfisols and double cropping in vertisols;

- with a long duration available effective rainy period, double cropping is preferable.

However, the crop varieties that are suitable for these cropping patterns also differ significantly. They are associated more with the soil type, and the wet and dry spells within the available effective rainy period. The following successful crop varieties under different conditions are identified.

- on alfisols, millets should be grown, and on vertisols, sorghum, maize, paddy-rice, etc., are more preferred crops:
- when the wet spells are  $> 7$  weeks and the duration of dry spells is  $\leq 70\%$  that of wet spells, then paddy-rice (with early rains) and maize (with late rains) are the preferred crops in vertisols. Under similar rainfall conditions, finger millet is the most suitable crop in alfisols:
- when the wet spells are  $\leq 7$  weeks, but are still more than dry spells, then maize or occasionally paddy-rice should be grown in vertisols and finger millet in alfisols:
- when the wet spells are less than dry spells then either pearl millet, sorghum, groundnut, castor, pigeonpea, cotton or finger millet are found to be more remunerative.

Some of these observations are based on subjective judgement (based on experimental experience) and are used to characterize the homogeneous groups identified in the latter study.

## CHAPTER 6

### AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS:

#### IV. CLASSIFICATION OF INDIA, SENEGAL AND UPPER VOLTA

##### 6.1 INTRODUCTION

The identification of raw data and the derivation of agroclimatic variables were presented in the previous three chapters. Here, the semi-arid tropics (SAT) of India, Senegal and Upper Volta in west Africa are classified into agronomically homogeneous zones using the 11 agroclimatic variables derived in Chapter 4 from data for 190 locations. For clarity this study is divided into two sections, with the following objectives:

1. to analyse the data from India, Senegal and Upper Volta in order to understand the position of each location relative to others by numerical taxonomic techniques;
2. to characterize the finite groups as relevant to farming system practices.

Numerical classification procedures present the position of each location relative to others according to specified criteria and each location by itself represents a separate group. These groups need not necessarily represent the relevant agronomically-homogeneous zones. These groups need minor modifications to be more relevant agronomically. However, such a process should not affect the basic structure of the groups obtained from the numerical analysis. It is important to characterize each group by agroclimatic variables and farming system practices. New locations can then be readily fitted into the groups, thereby aiding the transfer of new technology. The process involves a certain level of subjective judgement, but this can be kept to a minimum by careful use of some of the inferences made in the numerical classification.

The objective of this chapter is, therefore, to explore and understand the relationships between 190 locations in India, Senegal and Upper Volta

in order to arrange them into their relevant agronomically homogeneous zones.

## 6.2 METHODOLOGY – NUMERICAL TAXONOMIC PROCEDURES

Climatic classification procedures range from traditional descriptive (Koppen, 1936; Thornthwaite, 1948; Troll, 1965; Hargreaves, 1971; Papadakis, 1975; for more details see Chapter 2), to modern computer based numerical techniques (Sokal & Sneath, 1963; Moore & Russell, 1967; Cormack, 1971; Sneath & Sokal, 1973). The entire range can be found in use for climatic, as well as soil, biological, ecological and geological classifications (Harbough & Merriam, 1968; Arkley, 1976; Nix, 1975; Russell & Moore, 1976; Austin & Nix, 1978; Austin & Yapp, 1978; Russell, 1978). Sokal (1974) presented a classical treatise on purpose, principles, progress and prospects of classification.

The applicability of numerical taxonomic techniques to global climatic, bioclimatic or agroclimatic studies is not well known. However, any classification procedure involves a number of steps or strategies, from data collection through to interpretation of results. A comprehensive flow chart of these steps with alternative strategies and/or options are depicted in Fig. 6-1. The basic steps are:

1. identification of available raw data;
2. derivation of attributes (variables) that define a particular character of interest;
3. computation of similarity matrices, which integrate characters into a single entity;
4. grouping or classification of the locations using these attributes or similarity matrices;
5. interpretation of final results.

Details on the first two aspects are presented in the previous three chapters.

In Appendix F, an attempt is made to catalogue and discuss different methods of classification as they apply to climate and to identify a similarity metric that integrates the variables of continuous numerical data sets. A summary of the discussions are presented below.

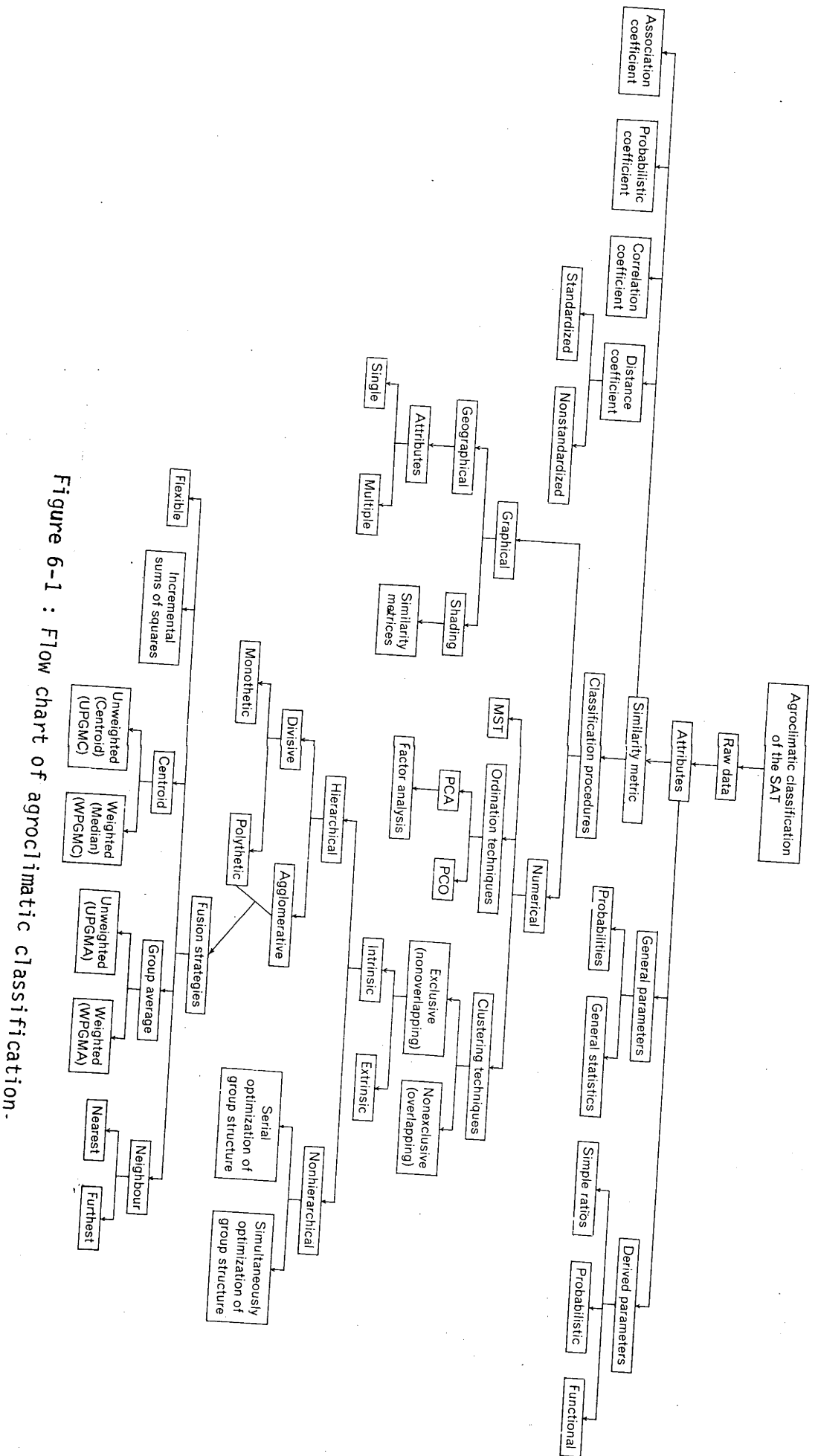


Figure 6-1 : Flow chart of agroclimatic classification.

### 6.2.1 Merits and demerits of graphical and numerical procedures

Classifications differ in many respects. In descriptive procedures, for example, it is not possible to handle many variables simultaneously. The limit for a class or group of variables is set at a discrete interval; thereafter, addition or removal of locations will not alter the position of the location in the classification, while in the numerical techniques, this is not so. No two numerical procedures give identical results. In the descriptive procedures, however, the variables that define a class or group differ, and therefore associated groups also differ unless the differentiating variables are linearly correlated. Internal homogeneity is low in the descriptive procedures but is relatively high in the numerical procedures. Using the descriptive procedures a specific area represents a continuum of a variable or group of variables and in the numerical procedures it presents a discrete or discontinuous area. In the descriptive procedures personal bias is more pronounced than in the numerical procedures. In both techniques, the differentiating characteristics or criteria used to form classes should contain maximum possible information to obtain better groups for classification. Because of these characteristics, in the broader zonation of world climates, descriptive procedures are the more useful of the two systems. Numerical procedures are more useful in the finite grouping of such zones or in agroclimatic classification. The major advantage of numerical procedures over descriptive procedures is the ease with which the variables can be integrated and locations grouped with minimum bias. The major weakness of numerical procedures is that no two methods give identical results and there is no established procedure for choice of optimal method. Also, with the change of data type (i.e., qualitative or quantitative), the choice of methods differs substantially. Consequently, in each case one has to try all the possible combinations and check which method is suitable for the available data. This procedure is both time-consuming and costly. Finally, any group formed must be validated subjectively, since there is no formal test of homogeneity or mis-classification.

### 6.2.2 Similarity measures for continuous numerical data sets

Among several similarity measures that are used in the integration of variables, the two procedures most commonly used with continuous numerical data sets are distance measures and correlation coefficients. Of the standardized distance measures, the Bray & Curtis and the Canberra measures involve at each stage only the pair of entities; while in the case of the Euclidean metric standardized by population s.d., and the mean character distance (MCD) standardized by population range (Gower metric) considers entire populations at each stage. The standardization procedure in the former group the similarity measures of some pairs gain undue weight and this is a disadvantage; the purpose of standardization is to bring the differences into a uniform scale. This standardization is not achieved, and as a result some groups get undue weight. Applicability of the Canberra metric is also limited to positive values. Some of the modifications suggested to enable this procedure to handle both positive and negative values appear to be invalid. Even though both the MCD standardized by range, and the Euclidean metric standardized by s.d. are mathematically sound (obey the triangle inequality), their magnitudes differ. This is because the former presents the first order absolute differences while the latter represents the second order squared (and its square root) difference. The correlation coefficient is not a correct measure to represent the true distance between any two locations in terms of their attributes. It does not obey the triangle inequality and perfect correlation could occur between non-identical attributes. This tendency of correlation limits its applicability when the extremes are highly correlated.

New methods of standardization are in no way superior to the conventional procedures, such as first order differences (MCD) by population range and second order differences (Euclidean metric) by population s.d.

A weakness in the transformation of data to linearity is that not only does it reduce the range of variation, but as in the Bray & Curtis and the Canberra measures, undue weight is acquired by some pairs of measures. In the case of continuous numerical data the two more appropriate similarity measures are the standardized (with s.d.) Euclidean metric of the second order differences and the Gower metric (MCD standardized by range) of the first order differences. In the present analysis these two techniques are used.



### 6.2.3 Applicability of numerical techniques for agroclimatic classification

Among the three numerical classification procedures, namely ordination, minimum spanning tree (MST) and clustering, MST could be used as a check rather than as a separate classification procedure.

#### 6.2.3.1 Ordination

Both principal component analysis (PCA) and principal coordinate analysis (PCO) under ordination are mathematically sound techniques. When the starting matrix consists of Euclidean distances, both give identical results. This means mathematically that both are similar, but PCO is more flexible using similarity measures. But both suffer from the same weakness: a difficulty in interpretation, as coordinates or components, are difficult to interpret in physical terms. A problem associated with ordination (PCA or PCO) using both correlation or covariance is that the mean of each station record does not influence the level of similarity between station records as these coefficients describe deviations about means. As a result stations with highly different means could be seen as identical. When the selected variables of any pair of locations are highly correlated, irrespective of their magnitude, ordination (particularly PCA) is less suitable. Consequently, ordination is an exploratory technique rather than a technique for grouping or for obtaining reasonable classes. Ordination can be used to generate new standardized variables that are fewer in number and contain less noise than the original variables. Also, fewer such variables explain the maximum variance in the data set. These new variables could be used in the computation of the similarity matrix and then calculation of clusters. The new variables can be used to describe the spatial distribution and to identify homogeneous zones with respect to the first few coordinates. In the present study, however, PCO was used to generate new attributes rather than as a classification procedure.

#### 6.2.3.2 Cluster techniques

There are several clustering procedures existing in the literature. The most appropriate procedures for numerical continuous data sets are hierarchical-nonoverlapping-agglomerative-polythetic techniques. Under these procedures there are eight fusion strategies, namely:

- NN : Single linkage or nearest neighbour;
- FN : Complete linkage or farthest neighbour;

- UPGMC: Centroid or unweighted pair group centroid;
- WPGMC: Median or weighted pair group centroid;
- UPGMA: Unweighted pair group method using arithmetic averages;
- WPGMA: Weighted pair group method using arithmetic averages;
- IS : Incremental sums of squares or minimum variance;
- FB : Flexible sorting ( $\beta = -0.25$ ).

In all the above strategies, the basic steps are similar. Beginning with the inter-individual similarity or distance matrix the methods fuse individuals or groups of individuals which are most similar and proceed from the initial stage of all individuals under individual groups to the final stage in which all individuals are in a single group. Out of these eight fusion strategies, two (NN and FN) do not give weight to the entire population of similarity matrix, and these are respectively categorised as space-contracting and space-dilating strategies. WPGMC, UPGMC, FB and IS are biased by the distance of a group that is currently formed. UPGMA is mathematically simple and sound; and gives equal weight to all the individuals in a group. In UPGMC if a small group fuses with a large one, the small group loses its identity. While FB and WPGMC are mathematically similar, FB is space-dilating and on the contrary WPGMC is a space-conserving strategy. IS and UPGMC are respectively space-dilating and space-contracting strategies. In terms of space conservation UPGMA, WPGMA and WPGMC are the more acceptable fusion strategies. According to the Cophenetic correlation coefficient, NN is the least acceptable strategy. IS is the least acceptable strategy according to the Bray-Curtis value, while UPGMA is the most acceptable fusion strategy irrespective of similarity metric, with WPGMA the second best. This is also true for the Cophenetic correlation coefficient under the majority of similarity metric. The Cophenetic correlation coefficient suggests that UPGMC and WPGMC are superior to WPGMA while WPGMC is still better than UPGMC. Therefore, according to these tests UPGMA is consistently superior to others. Next in order comes WPGMA and WPGMC.

All these tests emphasise the mathematical soundness of different

fusion strategies, but do not address problems of the level of mis-classification in the calculation in the clusters as such. Some times it is possible to discard a method completely because the results appear nonsensical. This type of subjective test also suggests that UPGMA, then WPGMA are the two fusion strategies with least mis-classifications. Surprisingly, IS with the Euclidean metric also produces acceptable clusters. This emphasises the fact that the above mentioned procedures are not in fact designed for the testing of clusters. However, in IS the results are not consistent with the other similarity metric but IS is also not a simple procedure mathematically as that of UPGMA.

From the above discussion it is apparent that, both mathematically and practically, the preferred fusion strategy for numerical continuous data sets is UPGMA, with WPGMA the second preference. In the present study, therefore, UPGMA and WPGMA are used. Finally, to make resulting groups more meaningful for the interpretation of results, as well as to facilitate the fitting of new locations into these groups, some level of subjective judgement is necessary.

### 6.3 DATA AND ANALYSIS

There are 11 agroclimatic variables used in this study, eight of which relate directly to agricultural production (s, G, C, W,  $\alpha$ , D,  $\beta$  and A) and three reflect local, regional and global dissimilarities. These variables were identified in Chapter 4. The 11 variables for 190 locations (71 in India, 59 in Senegal and 60 in Upper Volta) are subjected to some of the numerical classification procedures identified above. As the Indian data represent more arid locations compared to west African locations, only 71 out of the 80 possible locations are used in this analysis. The clustering techniques adopted are weighted and unweighted pair-group methods using arithmetic averages (WPGMA and UPGMA) in conjunction with the Gower metric and the standardized Euclidean metric. Flexible fusion strategy (FB) is also used. This procedure has been used by Nix (1975), Austin & Nix (1978) and Russell (1978). The analysis has been carried using the numerical TAXON packages on CYBER 77 and NPT/PDP-11/34 of CSIRO (Canberra).

## 6.4 RESULTS OF NUMERICAL ANALYSIS

### 6.4.1 Principal coordinate results

Table 6-1 presents the range of variance for the 11 agroclimatic variables over the first seven principal coordinates, and also details the correlation coefficients for individual variables at individual coordinates. The magnitude of these correlation coefficients signifies the extent of influence of each of the variables on different principal axes. Even though the variance for coordinates 3-7 is small, the correlation coefficient values of some of the variables are significant, which suggests that it is not always sensible to restrict analysis to a few coordinates based on variance. It is clear from these results that the spatial variation is mainly associated with G and that further sub-divisions are based on the level of dependability. Unfortunately, this method is unable to differentiate between the different elements defining the level of dependability, an important factor in agricultural production (Fig. 6-2).

### 6.4.2 Minimum spanning tree results

The general opinion about the minimum spanning tree technique is that it can be used to check mis-classifications formed in other classification procedures. However, even here some major mis-classifications are evident (Fig. 6-3).

### 6.4.3 Cluster results

Cluster analysis using the standardized Euclidean metric (Fig. 6-4) and the Gower metric (Fig. 6-5) with unweighted and weighted pair group methods using arithmetic averages (UPGMA and WPGMA) and flexible (FB) fusion strategies suggests that the clusters formed under UPGMA with the standardized Euclidean metric are preferable to the other 5 combinations; followed by the UPGMA - Gower metric and WPGMA - Euclidean metric combinations, respectively. It is also found that the clusters formed under the Euclidean metric, with UPGMA fusion strategy based on the data matrix of seven principal coordinates and 190 locations (Fig. 6-6), appear to be the most suitable over 11-variables with UPGMA - Gower metric (for 154 or 190 locations) or WPGMA - Gower metric (190 locations) (Fig. 6-7).

Figure 6-6 demonstrates the agroclimatic classification of the 190 locations. The main branches in this figure are depicted in Fig. 6-8, which also presents the mean pattern for the 11 agroclimatic variables together with the number of locations in each of these branches. It is

Table 6-1 : Contribution of different attributes expressed as correlation coefficient to the first 7 principal coordinates.

ATTRIBUTES	CORRELATION COEFFICIENTS						
PRINCIPAL COORDINATES:	1	2	3	4	5	6	7
$\delta$	+ .54	- .65	- .17	- .17	- .29	+ .34	+ .19
$\overline{G}$	- .96	- .03	+ .06	+ .03	- .02	+ .14	+ .02
C	+ .90	- .01	- .27	- .08	+ .28	+ .08	- .12
$\overline{W}$	- .92	- .03	- .29	+ .09	+ .17	+ .07	+ .09
$\alpha$	- .41	- .73	- .05	+ .45	- .07	+ .12	- .26
D	- .82	- .10	+ .26	- .35	+ .17	+ .21	- .17
$\beta$	+ .48	- .76	- .00	- .06	- .16	- .25	- .06
G'	- .40	+ .65	- .43	- .15	- .42	- .01	- .20
W'	- .81	- .23	- .47	+ .05	+ .16	- .11	+ .15
D'	- .58	- .64	- .07	- .40	+ .04	- .18	- .07
A	+ .90	+ .00	- .30	- .07	+ .24	+ .10	- .12
Variance (%)	53.7	22.0	6.9	5.1	4.6	2.9	2.2

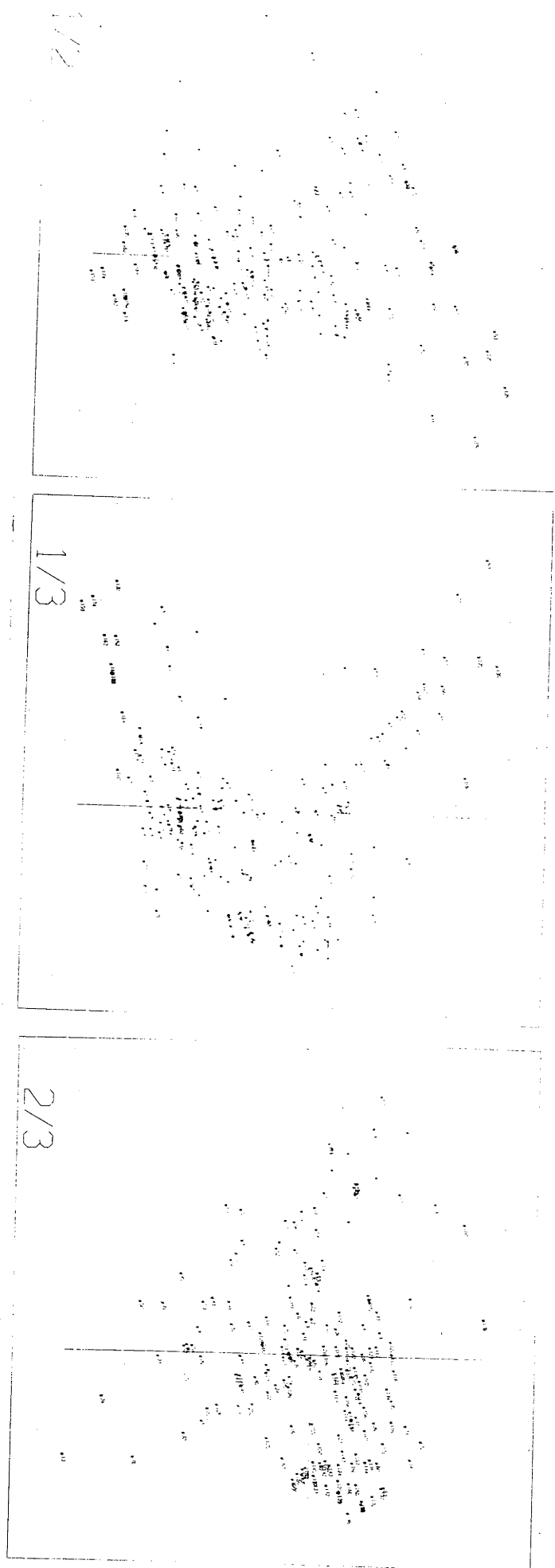
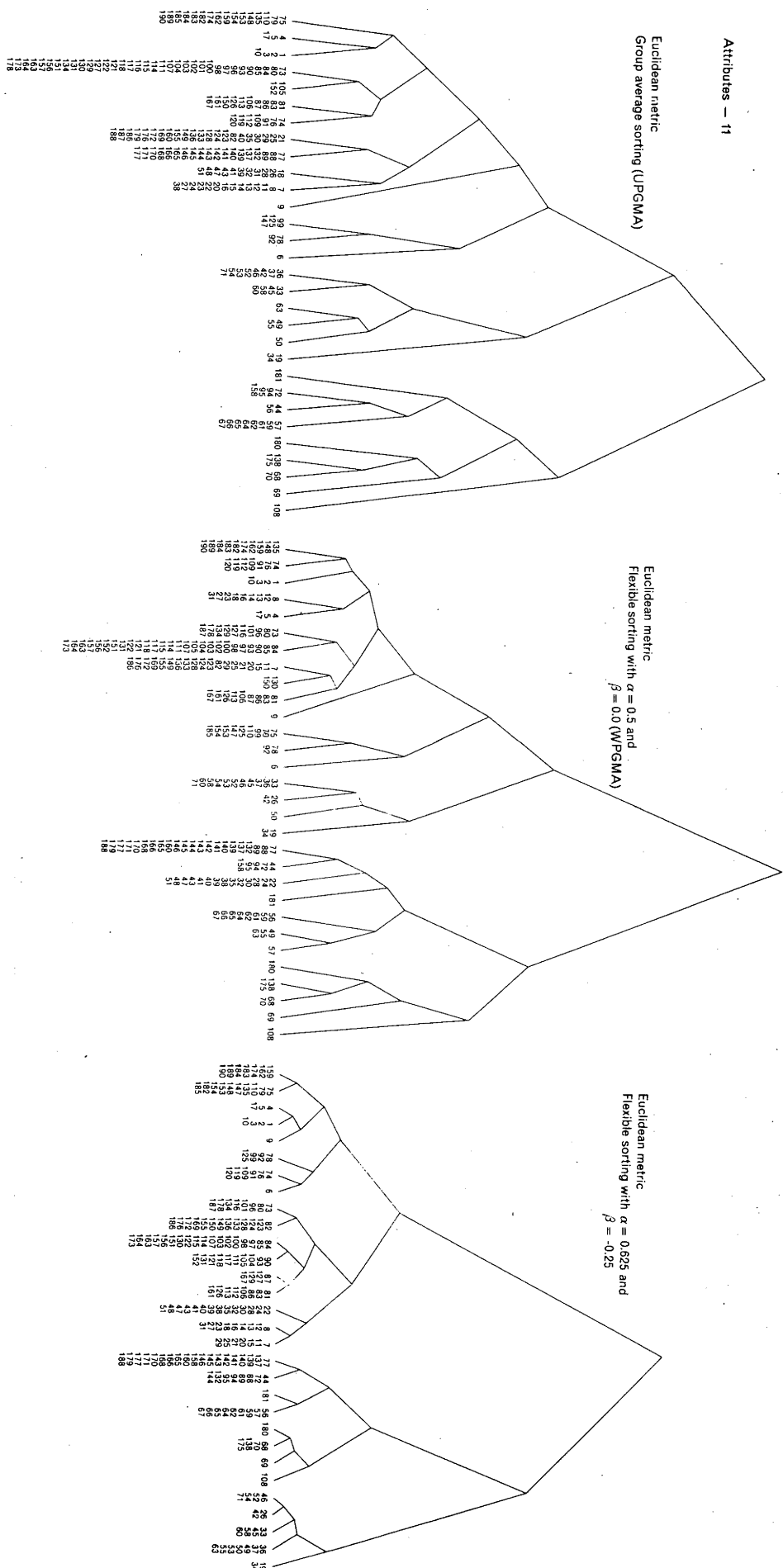


Figure 6-2 : Results of principal coordinate analysis (coordinates 1 versus 2, 1 versus 3 and 2 versus 3).



Attributes — 11





Attributes — 11

Gower metric  
Group average sorting (UPGMA)

Gower metric  
Flexible sorting with  $\alpha = 0.5$  and  $\beta = 0.0$  (WPGMA)

Gower metric  
Flexible sorting with  $\alpha = 0.625$  and  $\beta = -0.25$

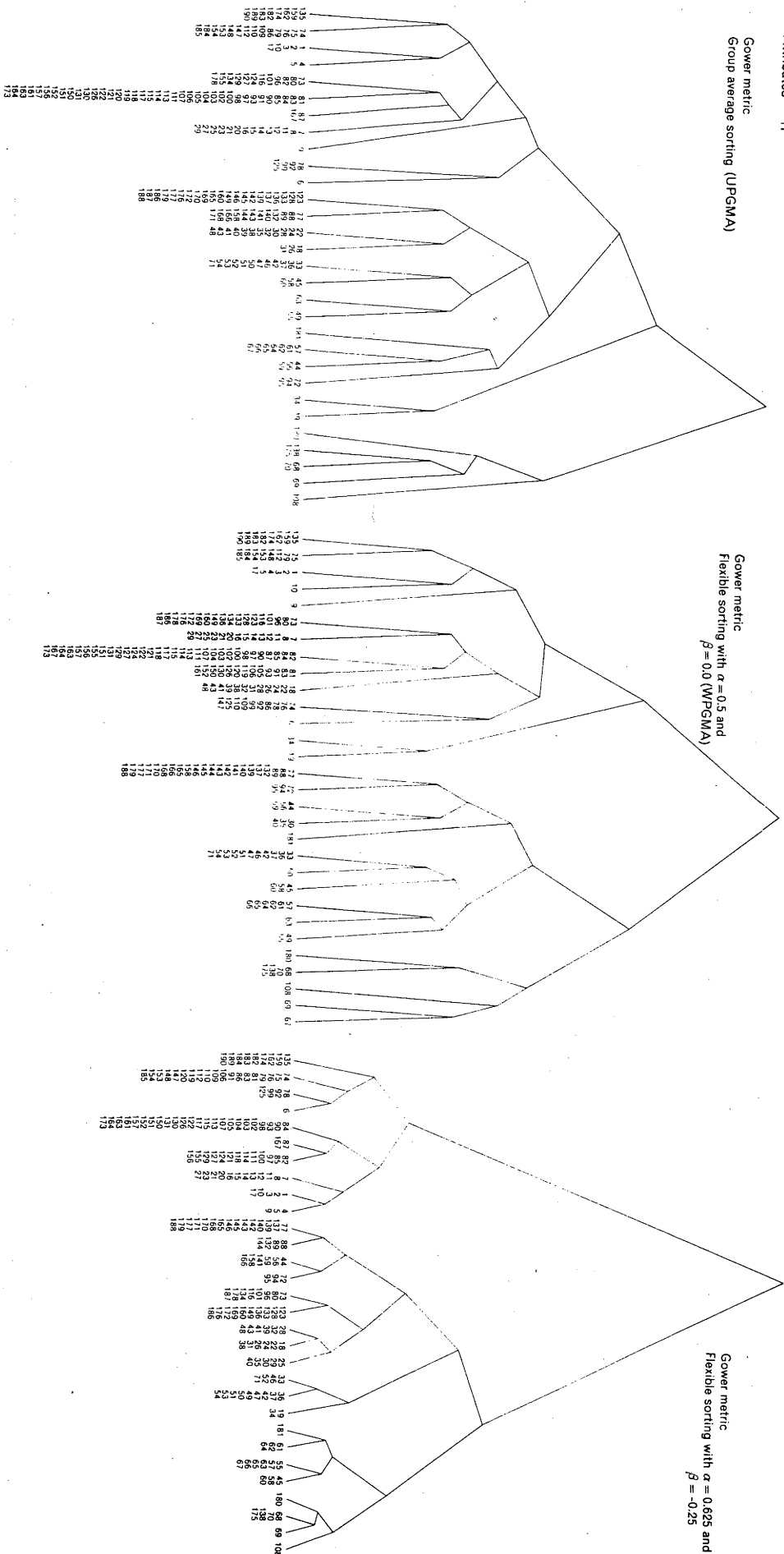


Figure 6-5 : Dendrograms of different fusion strategies with Gower metric (limited to 30 groups).

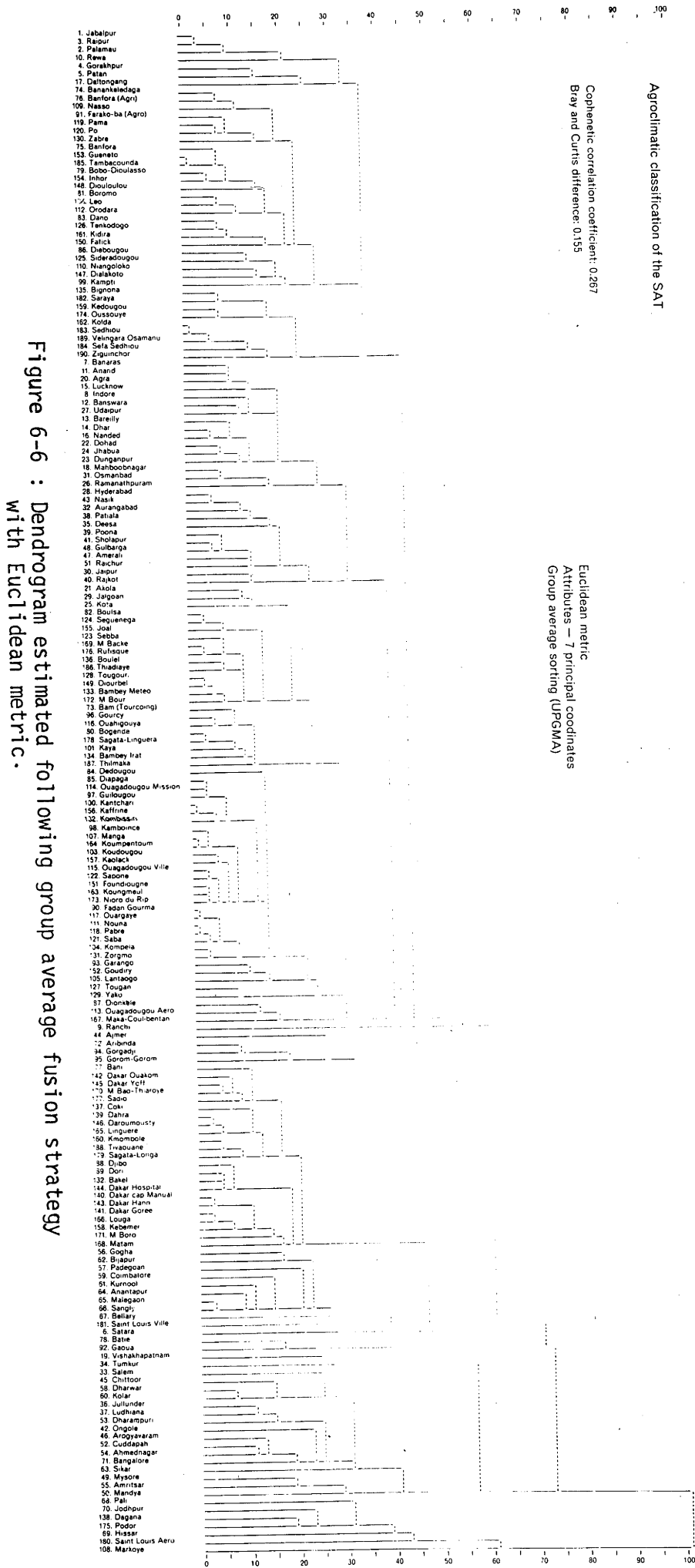
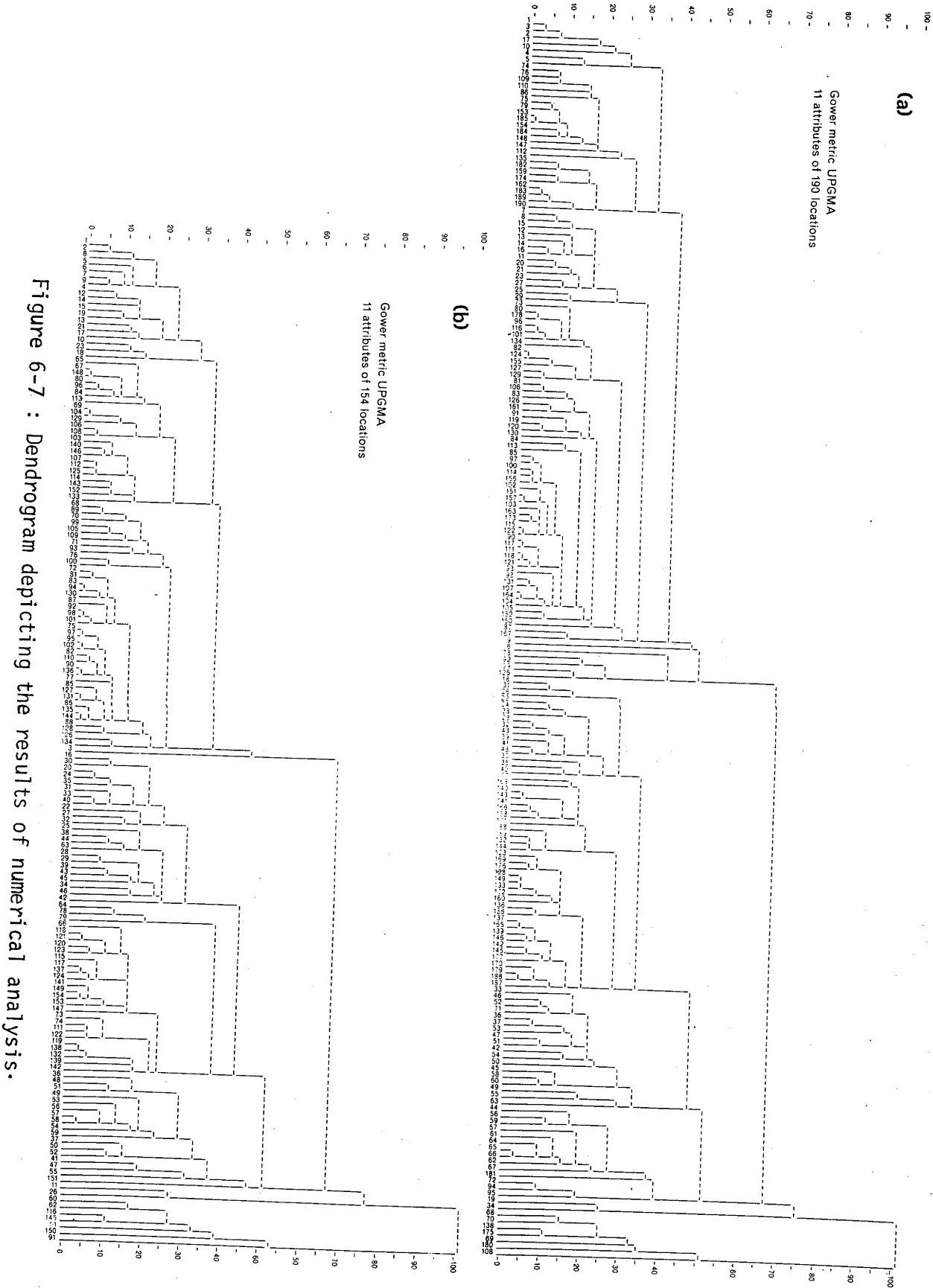
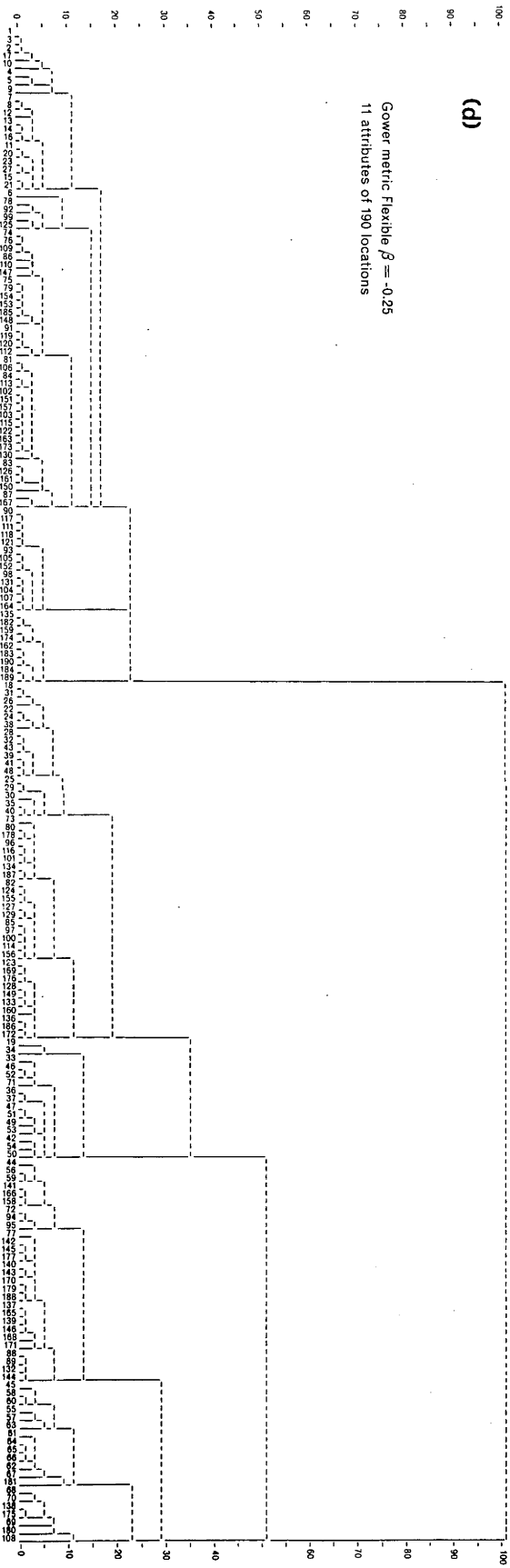


Figure 6-6 : Dendrogram estimated following group average fusion strategy with Euclidean metric.



cont.

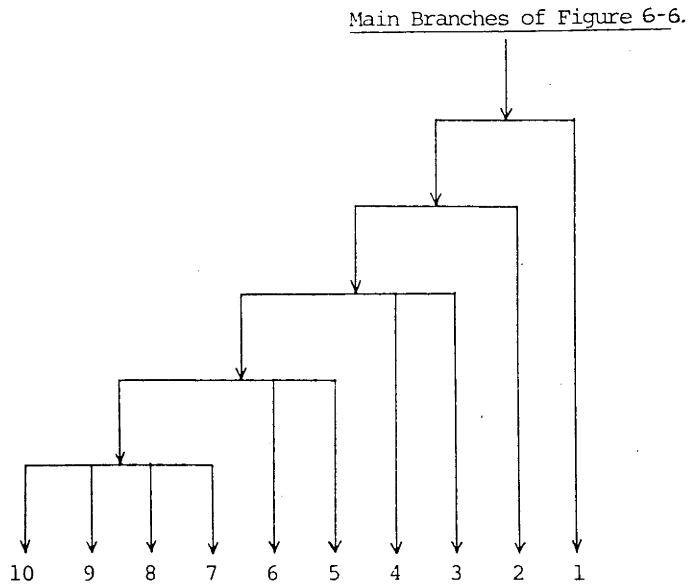


seen from this figure that at the first fusion, seven locations with very low G associated with high C and A are separated from the rest. At the next two fusions, three branches (2, 3 and 4) with high negative G' are separated; and in turn these three branches are separated from 7 to 10 by high C. Branches 5 and 6 are separated according to  $\delta$ . Branch 10 is separated from 7 to 9 by D while branches 7-9 are separated from each other by G.

According to Clifford & Stephenson (1975), "it is not always desirable to truncate each branch of a dendrogram at the same level. Though differential truncation involves subjective decision, it can be argued that objectivity is maintained if cut-off values are explicitly stated". Consequently, some of the locations are merged at different branches to reduce the number of groups, particularly for the SAT locations, otherwise each location will represent a separate group. The details on each of the branches presented in Fig. 6-8, together with the mean patterns of the agroclimatic variables, are presented in Figs. 6-9 to 6-14 and the respective locations for each of these groups are presented in Table 6-2.

The 190 locations are divided into two major classes. Seven locations in one group (Branch 1 in Fig. 6-8) and the remaining 183 locations in the other. The seven locations (68, 69, 70, 138, 175, 108 and 180) are arid (Chapter 2). Of these seven locations, three are in India (68, 69 and 70), three in Senegal (138, 175 and 180) and one is in Upper Volta (108). Numbers 1-71, 72-131 and 132-190 represent locations in India, Upper Volta and Senegal, respectively.

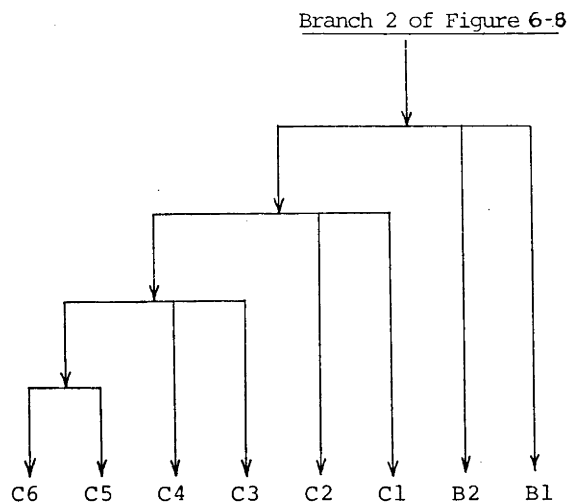
The 167 semi-arid locations are arranged into 58 groups. These results suggest that, with few exceptions, groups are separated primarily by G with values  $\leq 8$ , 8-13, 13-18, 18-21 and  $> 21$  weeks. The locations are also separated according to the magnitude of  $\delta$ . However, some of these groups at lower values of  $\delta$  ( $\leq 3$  weeks) are not clearly differentiated in terms of dependability related to the level of dry-seeding feasibility (Chapter 4). There are also few exceptions in terms of the level of water-logging hazards. If no significance in terms of agriculture is assigned to the magnitude of different values, these groups are perfectly acceptable, but in the present context the magnitude of  $\delta$ , particularly at the lower range, is significantly related to the dry-seeding feasibility level. This is a basic weakness of continuous data sets. Therefore, the groups presented in this section need to be further adjusted to obtain more



Branch No.	No. of Locations	Average values of the 11 agroclimatic attributes *										
		$\delta$	$\bar{G}$	C	$\bar{W}$	$\alpha$	$\bar{D}$	$\beta$	A	G'	W'	D'
1	7	2.6	2.8	169	2.6	1.1	3.8	1.8	74	2.1	-3.1	-1.8
2	18	5.7	10.3	73	3.8	2.6	5.2	3.4	35	-1.7	-0.4	0.5
3(D1)	1	2.1	18.4	27	7.1	2.0	7.1	3.0	00	-2.9	2.4	2.4
4(D2)	2	3.4	24.6	21	8.9	3.5	7.2	2.3	02	-6.3	2.5	0.8
5	10	4.3	5.7	101	2.7	1.8	3.9	2.6	50	0.8	-1.5	-1.0
6	27	1.9	9.6	63	3.4	1.5	4.9	2.0	27	-1.0	-2.4	-1.4
7	28	2.8	12.6	39	5.3	2.3	5.2	2.3	10	-0.2	0.6	0.5
8	55	1.8	16.9	21	5.8	2.1	5.9	1.8	03	2.9	-0.7	-0.4
9	41	2.1	22.2	14	8.9	2.4	6.6	1.8	00	1.3	2.7	0.4
10	1	2.9	16.4	23	7.5	3.4	3.7	1.8	00	0.7	2.8	-1.0

\*  $\delta, \bar{G}, \bar{W}, \alpha, \bar{D}, \beta, G', W' \text{ \& } D'$  are in weeks and C & A are in %.

Figure 6-8 : Main branches and associated average pattern of agroclimatic attributes (Figure 6-6).

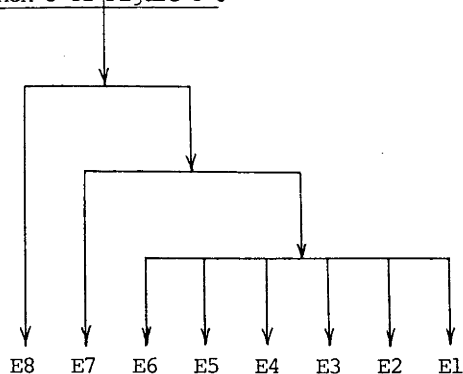


Branch No.	No. of Locations	Average values of the 11 agroclimatic attributes <sup>*</sup>										
		$\delta$	$\bar{G}$	C	$\bar{W}$	$\alpha$	$\bar{D}$	$\beta$	A	G'	W'	D'
B1	3	8.5	8.7	75	3.1	2.1	4.7	3.1	29	-0.8	1.9	0.0
B2	2	5.0	15.2	57	4.9	3.3	6.6	3.9	17	-5.7	0.2	1.9
C1	1	6.5	6.0	100	3.8	2.3	5.1	2.7	50	0.5	-0.9	0.4
C2	4	5.0	9.5	85	3.4	3.0	4.2	3.4	40	-2.2	-1.3	-0.4
C3	3	5.9	10.2	60	3.9	2.4	4.7	3.2	23	-0.9	-0.8	0.0
C4	1	5.6	11.2	58	3.7	2.2	6.0	3.2	24	-1.8	-1.0	1.3
C5	3	4.6	9.9	74	3.7	2.4	5.2	3.8	31	-1.9	-1.0	0.5
C6	1	4.7	11.8	71	3.9	3.1	5.2	3.9	32	-0.8	-0.6	0.5

\*  $\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$ ,  $\beta$ , G', W' & D' are in weeks; and A & C are in %.

Figure 6-9 : Branch 2 and associated groups along with the average pattern of agroclimatic attributes (Figure 6-8).

Branch 5 of Figure 6-8

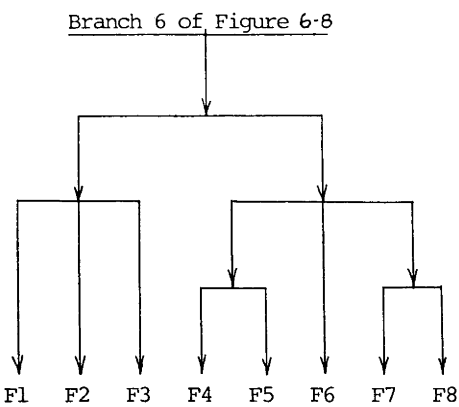


Branch No.	No. of Locations	Average values of the 11 agroclimatic attributes *										
		$\delta$	$\bar{G}$	C	$\bar{W}$	$\alpha$	$\bar{D}$	$\beta$	A	G'	W'	D'
E1	2	3.3	6.5	95	3.1	2.3	3.9	2.7	47	0.3	-1.6	-0.9
E2	1	5.6	6.2	87	2.3	1.4	4.3	2.9	44	0.9	-2.4	-0.4
E3	1	4.6	6.5	82	3.0	1.8	3.9	2.2	40	0.9	-1.7	-0.8
E4	1	4.5	6.1	97	2.3	2.0	3.3	2.6	45	0.6	-2.4	-1.4
E5	1	4.8	5.2	104	2.7	1.7	3.7	2.5	52	1.2	-2.0	-1.0
E6	2	4.8	5.3	114	2.1	1.8	3.7	3.0	60	0.7	-2.6	-1.1
E7	1	3.7	4.0	118	2.4	1.9	2.8	2.3	60	1.9	-2.3	-1.9
E8	1	2.7	6.1	108	3.4	1.7	5.7	2.4	50	0.1	3.0	-0.7

\*  $\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$ ,  $\beta$ , G', W' & D' are in weeks and C & A are in %.

Figure 6-10 : Branch 5 and associated groups along with the average pattern of agroclimatic attributes (Figure 6-8).

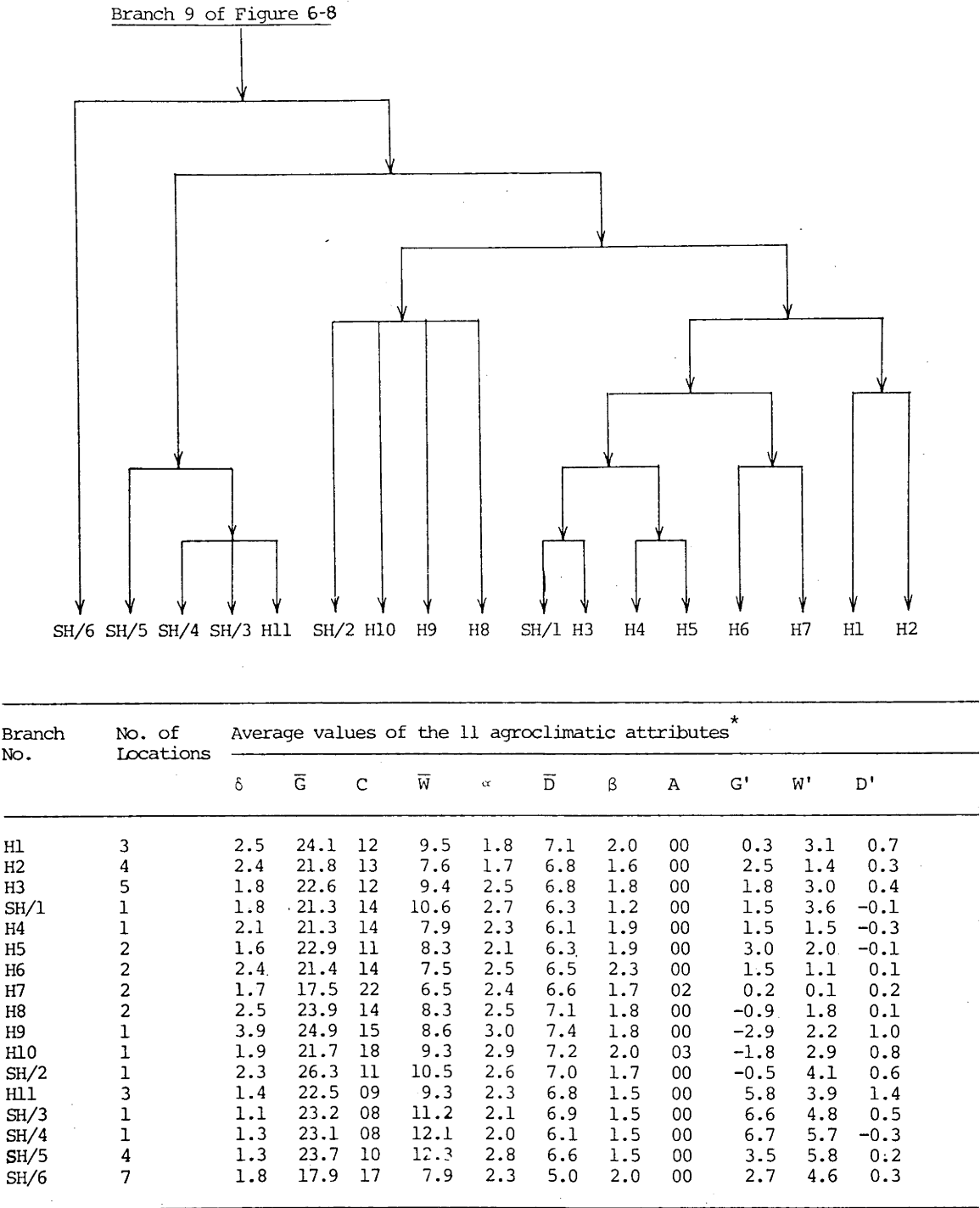




Branch No.	No. of Locations	Average values of the 11 agroclimatic attributes*										
		$\delta$	$\bar{G}$	C	$\bar{W}$	$\alpha$	$\bar{D}$	$\beta$	A	G'	W'	D'
F1	1	1.5	7.6	67	3.6	1.8	3.7	2.1	30	0.9	-1.1	-1.1
F2	1	1.8	7.0	86	2.5	1.2	4.2	2.5	47	0.2	-3.9	-2.2
F3	2	1.7	9.0	61	2.7	1.3	3.9	1.9	27	0.2	-3.7	-2.5
F4	5	2.3	11.5	56	4.1	1.9	5.7	2.2	23	1.9	-2.3	-0.7
F5	7	2.0	12.2	47	4.1	1.5	5.7	1.7	14	-1.2	-2.3	-0.7
F6	4	2.1	11.2	47	3.3	1.5	4.7	2.1	12	-0.4	-3.1	-1.7
F7	5	2.3	9.1	71	3.9	1.7	5.0	2.1	32	-0.9	-2.5	-1.4
F8	2	1.7	9.3	66	3.1	1.4	5.5	1.8	29	-0.8	-3.0	-0.9

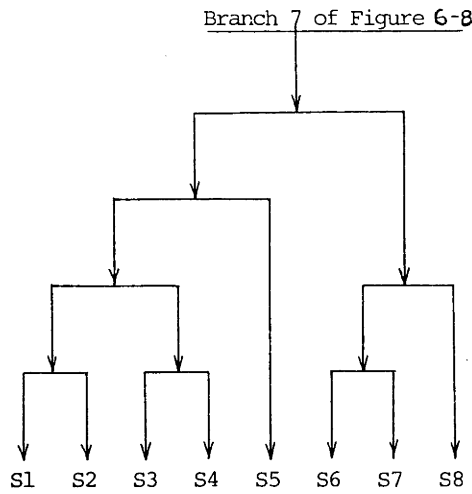
\*  $\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$ ,  $\beta$ , G', W' & D' are in weeks and C & A are in %.

Figure 6-11 : Branch 6 and associated groups along with the average pattern of agroclimatic attributes (Figure 6-8).



\*  $\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$ ,  $\beta$ , G', W' & D' are in weeks and C & A are in %.

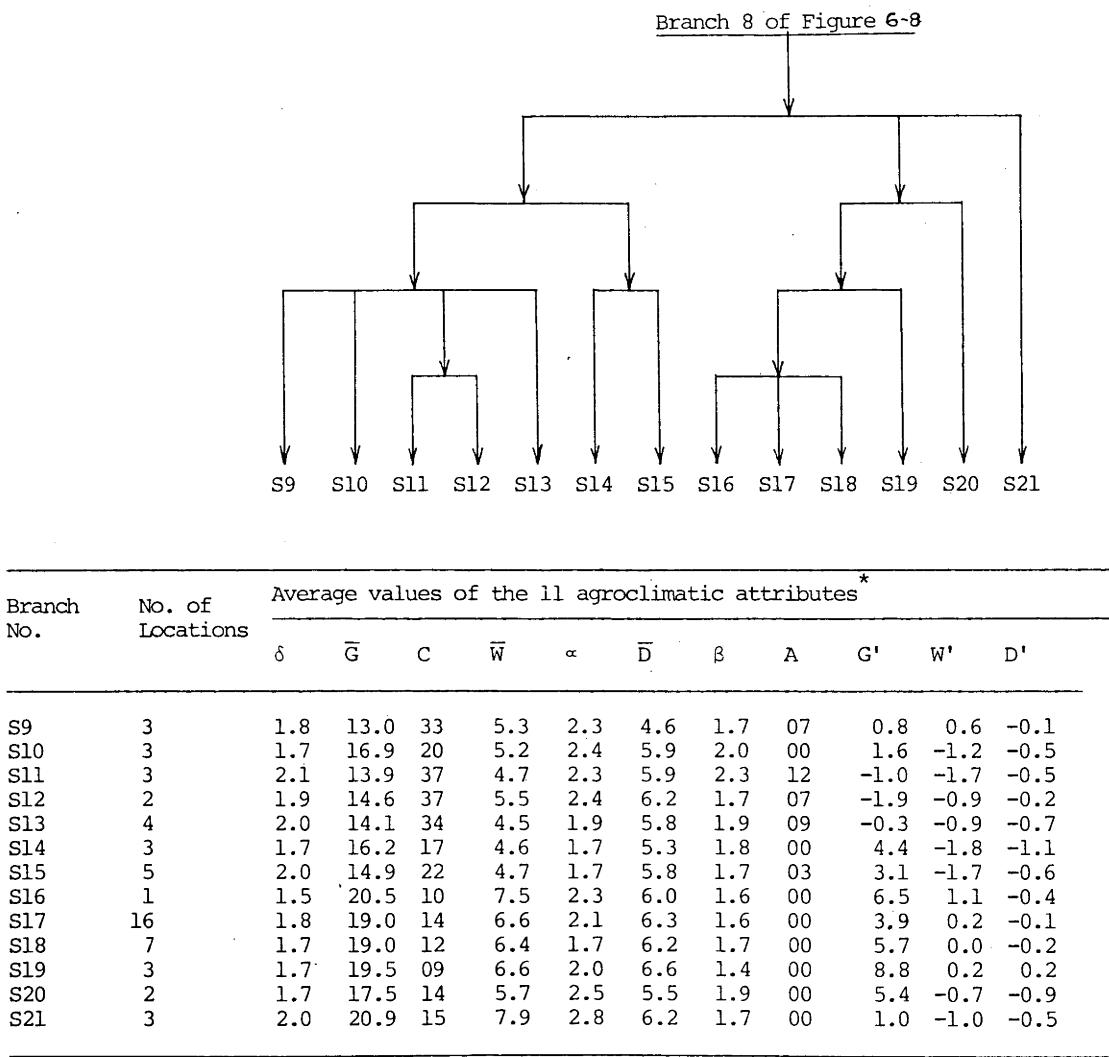
Figure 6-12 : Branch 9 and associated groups along with the average pattern of agroclimatic attributes (Figure 6-8).



Branch No.	No. of Locations	Average values of the 11 agroclimatic attributes <sup>*</sup>										
		$\delta$	$\bar{G}$	C	$\bar{W}$	$\alpha$	$\bar{D}$	$\beta$	A	G'	W'	D'
S1	4	1.5	14.8	24	6.6	2.1	5.2	2.0	03	2.1	1.9	0.5
S2	3	1.6	14.6	27	6.4	2.2	5.5	1.9	04	1.4	1.7	0.8
S3	3	2.4	15.4	28	6.5	2.5	5.3	2.3	04	-0.4	1.7	0.6
S4	3	2.2	13.5	36	5.4	2.2	5.4	2.3	07	-0.5	0.7	0.7
S5	3	3.4	14.9	35	5.3	2.6	5.9	2.7	08	-1.8	0.6	1.2
S6	5	2.7	11.6	51	4.4	2.3	5.1	2.6	16	-1.3	-0.3	0.4
S7	5	3.9	10.5	61	3.6	2.2	5.0	2.8	23	-1.3	-1.1	0.3
S8	2	3.5	9.8	50	3.9	2.4	4.2	2.1	15	0.5	-0.7	-0.5

\*  $\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$ ,  $\beta$ , G', W' & D' are in weeks and C & A are in %.

Figure 6-13 : Branch 7 and associated groups along with the average pattern of agroclimatic attributes (Figure 6-8).



\*  $\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$ ,  $\beta$ , G', W' & D' are in weeks and C & A are in %.

Figure 6-14 : Branch 8 and associated groups along with the average pattern of agroclimatic attributes (Figure 6-8).

Table 6-2 : Location numbers of different groups in Figures 6-8 to 6-14.

Group	Location	Group	Location
B1	49,50,55	H9	99
B2	19,34	H10	147
C1	63	H11	162,184,189
C2	33,45,58,60	SH/1	148
C3	36,37,53	SH/2	110
C4	42	SH/3	183
C5	46,52,54	SH/4	190
C6	71	SH/5	135,159,174,182
E1	56,62	SH/6	1,2,3,4,5,10,17
E2	57	S1	7,11,15,20
E3	59	S2	8,12,27
E4	61	S3	13,14,16
E5	64	S4	22,23,24
E6	65,66	S5	18,26,31
E7	67	S6	28,32,35,38,43
E8	181	S7	39,41,47,48,51
F1	44	S8	30,40
F2	95	S9	21,25,29
F3	72,94	S10	82,124,155
F4	77,142,145,170,177	S11	123,169,176
F5	137,139,146,160,165	S12	136,186
	179,188	S13	128,133,149,172
F6	88,89,132,144	S14	73,96,116
F7	140,141,143,158,166	S15	80,101,134,178,187
F8	168,171	S16	84
H1	74,76,109	S17	85,97,98,100,102,103,
H2	91,119,120,130		107,114,115,122,151,
H3	75,79,153,154,185		156,157,163,164,173
H4	81	S18	90,104,111,117,118,
H5	106,112		121,131
H6	83,126	S19	93,105,152
H7	150,161	S20	127,129
H8	86,125	S21	87,113,167

meaningful groups related to agronomy, as presented in Chapter 5. This extra refinement is attempted in the next section using some of the above inferences, together with inferences made in Chapters 4 & 5.

## 6.5 BASIC CRITERIA FOR THE AGROCLIMATIC CLASSIFICATION

The 190 locations are arranged into arid, semi-arid and sub-humid zones based on a modified Thornthwaite approach (Chapter 2). The basic characteristics of these zones in terms of agroclimatic variables are surprisingly different. For example, in the arid zone, the available effective rainy period is  $\leq 5$  weeks with an aridity index of  $> 60\%$ . In the sub-humid zone, the wet spells are  $> 7$  weeks with dry spells being  $\leq 70\%$  of wet spells, within an average available effective rainy period of  $> 16$  weeks and with an aridity index  $\leq 5\%$ . Also, wet spells constitute  $\geq 40\%$  of the available effective rainy period and dry spells constitute  $\leq 30\%$  of the effective rainy period.

The two most important parameters that have a bearing on agriculture, as observed in Chapter 5, are the mean available effective rainy period ( $G$ ) and the s.d. of commencement time of sowing rains ( $s$ ). Therefore, the semi-arid tropics are divided into five zones based on the average available effective rainy period ( $G$ , Table 6-3). The ranges shown in Table 6-3 agree with the numerical classification branches (Fig. 6-8).

The five zones mentioned above correspond to 5 major cropping patterns, namely single; single/inter; inter/double; double, with a medium duration (90-120-day) kharif; and double, with long duration (120-150-day) kharif. These patterns represent a highly dependable rainfall situation and need to be modified with less dependable rainfall. For example, in zone 2, with undependable condition ( $s > 3$  weeks), in years of good, early rains, a short duration pulse crop followed by a late kharif cereal crop can be grown (Chapter 5). In years of late rains, a late kharif only is possible. This practice not only increases productivity by utilizing the initial rains, but also reduces soil erosion. Therefore, based on the level of dependability ( $s$ ), each of the five zones are further divided into five sub-zones (Table 6-3). The crop species and cultivars with different levels of drought tolerance are differentiated by the proportion of wet and dry spells within the effective rainy period. For example, pearl millet, being less affected by frequent droughts, is more suitable in the

Table 6-3 : Basic criteria for the sub-division of regions into zones and sub-zones.

Zone No.	Limits ( $\bar{G}$ , weeks)	Sub-zone No.	Limit ( $\delta$ , weeks)
0	Arid zone		
1	$\leq 8$	5	$\leq 1.5$
2	8-13	4	1.5-2.0
3	13-18	3	2.0-3.0
4	18-21	2	3.0-6.0
5	$>21$	1	$>6.0$
6	Sub-humid zone		

sub-zones with a higher proportion of dry spells. These can be quantified as either  $W < 3$  weeks, or  $W < D$  in association with  $D > 5$  weeks, or  $W < G/3$ . Similarly, maize, being less drought-tolerant (yields will be substantially reduced by frequent dry spells [Hiller et al., 1974]), is more suitable in sub-zones with wet spells ( $> 5$  weeks) longer than dry spells. In between these two zones, sorghum is more suitable. The level of inputs into each of the zones also, depends upon the risk level (A). Areas with higher coefficients of variation (c.v.) (C) and  $\delta$ , reflect a high variability in the cessation times of rains and this highlights the risk associated with particular cropping practices. Regions where the available effective rainy period is short with high variation in cessation times of rains are suitable for growing mixtures of crops which reach maturity over different periods of time (either different cereals, or pulse and cereal that have less competition or adverse effects on yields). For example, two of the most common cereal mixtures are a 75-day pearl millet with a 90 to 100-day sorghum or a 75-day cowpea (pulse) with a 90 to 100-day sorghum or millet (cereal). Therefore, by utilizing characteristics of different agroclimatic variables the sub-zones are further divided into groups and sub-groups wherever possible (Table 6-4), all of which form a class. To make the groups and sub-groups more systematic, large data sets both crops and agroclimatic variables are essential, and these are not available to the author. At a future date when such information is available, the quantification of groups and sub-groups similar to that of zones and sub-zones could be attempted. If a class contains more than one location, then the lowest and the highest values for each agroclimatic variable in each sub-group are also shown in Table 6-4.

The arid and sub-humid zones, represented by zones 0 and 6, respectively, at zone level, are further divided according to dependability ( $\delta$ ) at sub-zone level (Table 6-3) and according to other variables at group and sub-group levels. However, these may not represent true homogeneous zones for fodder production in arid zone and wet-land agriculture (e.g., sugarcane, paddy-rice) in sub-humid zones, as criteria used to derive the agroclimatic variables applied to dry-land crops. Under arid zones, the water requirement for pastures are far less than for dry-land food crops (McCowen, 1981a). Similarly, in sub-humid zones, the water requirements for paddy-rice or sugarcane are far greater than for dry-land crops. Therefore, in the sub-division of arid and sub-humid



Table 6-4 : Agroclimatic classification results (India, Senegal &amp; Upper Volta).

Class	R	Agroclimatic attributes*								Location No. (see Figure 6-6)
		$\delta$	G	C	W	$\alpha$	D	B	A	
Arid zone:										
0211	-	5.9	2.0	170	2.1	1.4	3.0	1.4	74	69
0311	L	2.4	2.3	191	2.3	0.7	4.0	1.9	81	138, 175
	H	2.6	2.3	204	2.3	1.5	4.5	2.2	81	
0321	L	2.0	2.6	157	2.7	1.1	3.3	2.1	73	68, 70
	H	2.1	3.0	170	2.9	1.5	4.5	2.3	73	
0411	-	1.8	2.9	179	3.7	0.4	5.3	0.8	75	180
0511	-	1.2	4.6	111	2.0	1.2	2.3	1.6	61	108
Semi-arid zone:										
1111	-	8.7	7.0	80	2.8	1.6	4.7	2.7	38	55
1112	-	6.5	6.0	100	3.8	2.3	5.1	2.7	50	63
1211	-	3.7	4.1	118	2.4	1.9	2.8	2.3	60	67
1212	L	4.7	5.1	108	2.0	1.7	3.6	2.9	60	65, 66
	H	4.9	5.6	120	2.2	1.9	3.7	3.1	60	
1231	L	3.7	5.2	104	2.7	1.7	3.7	2.5	52	62, 64
	H	4.8	6.0	107	2.9	2.3	4.0	3.0	53	
1232	L	4.5	6.1	87	2.3	1.4	3.3	2.6	44	57, 61
	H	5.6	6.2	97	2.3	2.0	4.3	2.9	45	
1233	L	4.6	6.5	82	3.0	.8	3.9	2.2	40	59, 60
	H	4.8	7.6	96	3.3	.7	4.0	3.2	45	
1331	-	2.7	6.1	108	3.4	1.7	5.7	2.4	50	181
1332	-	3.0	6.9	84	3.3	2.3	5.7	2.3	42	56
1411	-	1.8	7.0	86	2.5	1.2	4.2	2.5	47	95
1511	-	1.5	7.6	67	3.6	1.8	3.7	2.1	30	44
2111	L	8.2	9.2	72	3.0	2.2	4.2	2.9	22	49, 50
	H	8.7	10.0	72	3.7	2.5	5.2	3.6	27	
2112	-	6.1	9.6	74	3.6	2.6	4.4	3.2	30	53
2211	L	5.0	8.9	81	3.7	2.8	3.8	3.0	42	45, 58
	H	5.3	9.0	92	3.6	3.1	4.3	3.7	44	
2221	L	4.2	9.2	71	3.4	2.0	4.4	2.8	30	51, 52, 54
	H	5.1	10.3	81	3.6	2.5	5.6	3.7	33	
2222	L	3.8	10.1	63	1.9	2.4	4.6	3.5	30	33, 46, 71
	H	4.7	12.5	71	4.0	3.3	5.2	4.2	32	
2231	L	3.5	10.6	58	3.7	2.1	5.2	2.6	23	42, 48
	H	5.6	11.2	61	3.9	2.2	6.0	3.2	24	
2232	L	3.5	9.4	57	3.4	2.0	4.8	3.0	24	41, 47
	H	4.0	11.3	64	3.6	2.4	5.0	3.2	26	
2241	L	4.1	10.3	48	3.6	2.0	4.3	2.6	15	36, 37, 39
	H	5.9	12.1	54	4.1	2.5	5.3	3.2	20	
2242	-	4.0	10.1	45	4.2	2.4	4.1	1.8	11	30
2311	L	2.4	8.2	81	3.7	1.5	4.6	2.0	38	158, 166
	H	2.5	8.4	82	3.8	1.8	5.1	2.4	38	
2312	L	2.2	9.1	67	3.7	1.7	4.9	1.9	36	140, 141
	H	2.3	9.3	69	4.1	1.8	5.1	2.2	37	
2321	L	2.2	10.6	58	3.6	1.7	5.2	1.9	22	77, 142, 143, 145
	H	2.5	11.8	59	4.1	2.1	5.8	2.7	26	
2331	L	2.1	9.6	45	3.1	1.5	4.3	1.8	13	40, 89, 144
	H	3.0	11.2	55	3.7	2.4	4.8	2.4	19	
2332	L	2.2	9.4	39	3.7	1.5	4.8	1.7	11	28, 35, 43, 146, 170, 176
	H	3.0	13.0	54	4.8	2.7	5.9	2.8	20	
2341	-	2.2	12.8	36	5.0	2.4	4.4	1.9	07	29
2411	-	2.0	8.6	65	2.9	1.1	3.9	1.8	25	72
2412	L	1.7	8.8	62	3.2	1.2	5.4	1.2	26	168, 171
	H	1.8	9.9	71	3.6	1.6	5.5	2.4	31	
2421	L	1.9	10.9	55	3.7	1.3	5.5	1.3	19	137, 139, 165
	H	2.0	11.2	56	3.9	1.5	6.0	2.0	20	
2422	L	1.9	11.0	41	3.3	1.4	4.5	2.1	04	88, 132
	H	2.0	11.9	53	3.4	1.6	4.9	2.3	12	
2423	L	1.8	10.7	45	4.2	2.0	5.2	1.7	13	38, 179
	H	1.8	12.6	56	4.9	2.2	5.6	2.8	19	
2511	-	1.4	9.4	56	2.4	1.5	3.8	2.0	30	94
2521	-	1.4	12.2	37	5.7	2.1	4.5	1.4	08	25

3211	-	5.6	13.7	63	4.5	3.3	6.1	3.7	19	34
3212	-	4.4	16.7	50	5.3	3.3	7.1	4.2	14	19
3221	-	4.6	13.4	39	5.3	2.5	5.8	2.9	09	26
3311	L	2.1	13.2	22	4.2	1.5	5.3	1.4	04	31, 32, 133, 134, 149,
	H	3.0	15.5	45	5.0	2.7	6.1	2.6	12	160, 169, 187
3321	L	2.1	13.1	21	5.3	2.1	5.4	1.8	00	18, 23, 27, 136, 155
	H	2.9	16.6	36	5.8	2.7	6.1	2.6	06	
3331	L	2.1	15.2	25	6.2	2.4	5.2	2.3	02	12, 13, 16
	H	2.3	15.9	30	6.9	2.6	6.1	2.5	05	
3332	-	2.1	17.7	16	6.6	2.3	6.1	1.6	00	157
3411	L	1.6	13.2	27	4.7	1.9	5.2	1.7	05	24, 123, 128, 172, 186
	H	1.9	15.4	37	5.7	2.5	6.3	2.5	11	
3412	L	1.6	14.9	16	4.0	1.5	5.2	1.7	00	73, 80, 82, 96, 101,
	H	1.8	17.4	21	5.1	1.4	6.0	2.2	00	116, 124, 178
3421	L	1.6	17.1	13	5.7	1.9	5.5	1.4	00	129, 150, 151, 156,
	H	1.8	17.9	24	6.6	2.6	6.6	2.0	04	161
3431	L	1.7	14.0	26	5.2	2.0	4.9	1.7	03	11, 14, 21, 22
	H	1.9	15.2	37	6.4	2.5	5.5	2.4	06	
3432	-	1.9	15.5	21	7.2	2.4	5.0	1.7	01	15
3511	-	1.0	13.3	27	5.9	2.0	5.1	1.9	08	20
3521	L	1.3	16.4	19	7.0	2.1	5.3	2.0	00	7, 8
	H	1.4	16.5	21	7.0	2.2	6.0	2.1	00	
4311	-	2.1	18.4	27	7.1	2.0	7.1	3.0	00	6
4321	L	2.1	18.7	12	6.1	1.6	6.0	1.5	00	102, 114, 117
	H	2.1	19.9	16	6.6	2.3	6.3	1.7	00	
4322	L	2.1	19.9	13	7.2	1.6	6.0	1.1	00	103, 113, 119, 126,
	H	2.6	20.8	15	7.3	3.0	6.7	2.0	00	130
4411	L	1.6	18.5	09	5.7	1.6	5.5	1.4	00	85, 90, 93, 97, 100,
	H	1.9	20.3	17	7.3	2.4	6.9	2.1	00	104, 105, 107, 111, 115,
										121, 122, 127, 163, 164, 173
4421	-	2.0	20.1	19	8.2	3.0	5.7	2.1	00	167
4511	L	1.4	18.8	09	5.9	1.6	5.9	1.0	00	98, 118, 131, 152
	H	1.5	20.2	12	6.8	2.1	6.6	1.7	00	
4512	-	1.5	20.5	10	7.5	2.3	6.0	1.6	00	84
5211	L	3.9	23.7	15	8.6	3.4	7.4	1.8	00	78, 99
	H	3.9	24.9	24	8.6	3.8	7.4	2.4	03	
5311	L	2.1	21.3	13	7.7	2.3	6.1	1.5	00	81, 83, 125
	H	2.8	23.8	15	7.9	2.6	7.1	2.6	00	
5312	L	2.1	22.1	10	8.2	1.5	6.9	1.7	00	74, 76, 86, 91, 92,
	H	2.7	25.5	18	10.0	3.3	7.1	2.3	00	109, 120
5411	L	1.6	21.4	10	7.9	2.3	5.8	1.5	00	75, 79, 87, 106, 147,
	H	2.0	24.8	18	9.7	2.9	7.2	2.0	00	153, 154, 184, 185
5511	-	1.2	23.6	10	8.3	2.0	6.0	2.2	00	112
5521	L	1.3	22.5	08	10.4	2.1	6.7	1.3	00	162, 189
	H	1.3	22.8	09	10.8	2.3	6.9	1.6	00	
<u>Sub-humid zone:</u>										
6311	-	2.9	16.4	23	7.5	3.4	3.7	1.8	00	9
6321	L	2.5	18.3	19	8.9	2.6	5.1	2.2	00	4, 5
	H	2.7	18.5	21	10.0	3.0	5.5	2.6	00	
6331	-	2.3	26.3	11	10.5	2.6	7.0	1.7	00	110
6411	-	1.7	16.9	26	9.0	2.1	4.3	1.8	04	17
6421	-	1.6	18.9	13	9.9	1.9	5.0	1.7	00	3
6431	-	1.8	21.3	14	10.0	2.7	6.3	1.2	00	148
6511	-	1.1	16.1	14	8.8	1.8	4.5	2.0	00	10
6521	L	1.3	18.3	14	9.3	2.1	5.0	1.7	00	1, 2
	H	1.5	18.5	15	9.8	2.3	5.3	1.9	00	
6531	L	1.1	22.1	15	11.2	2.0	6.1	1.3	00	135, 159, 174, 182,
	H	1.5	25.4	12	13.1	2.7	6.9	1.6	00	183, 190

<sup>e</sup> The four numbers of a class from left to right respectively represent zone, sub-zone, group and sub-group numbers.

<sup>f</sup> L and H respectively represent the lowest and the highest value of an attribute in that class.

<sup>g</sup>  $\bar{G}$ ,  $\bar{W}$ ,  $\bar{C}$ ,  $\bar{D}$ ,  $\bar{A}$  are in weeks and  $\bar{C}$  and  $\bar{A}$  are in %.

zones. the basic criteria used to derive the effective rainy period, as well as wet and dry spells, needs to be modified, and is beyond the scope of the present study. However, for the comparison of the SAT with arid and sub-humid situations the results obtained in this study are discussed relative to crop production. These classes are also presented in Table 6-4. The spatial distribution of the classes presented in Table 6-4 are depicted in Figs. 6-15 and 6-16 for India, and Senegal and Upper Volta, respectively. These results are discussed below.

#### 6.6 COMPARATIVE STUDY OF GROUPS IN TABLE 6-4 AND FIGURE 6-6

Some of the groups presented in Table 6-4 differ from those groups presented in Fig. 6-6, as discussed in an earlier section. The differences are not significant, but the groups in Table 6-4 are more agronomically relevant than the groups in Fig. 6-6, particularly where dry-seeding feasibility or the level of water-logging hazards are concerned.

In the above case it may be asked why use numerical taxonomic procedures at all? The basic utility of the numerical procedures, particularly with continuous numerical data sets, is that they clearly demonstrate which variables differentiate the locations at primary or secondary levels. This separation is clearly evident in an earlier section with the two primary variables  $G$  and  $\delta$ . However, the groups are not appropriate to the level of dry-seeding presented in Chapter 4 with regard to  $\delta$ . The importance of such clarity is evident from the experimental results. For example, at Hyderabad, with  $\delta = 2.9$  weeks, the research station results indicate the feasibility of dry-seeding (less frequently practiced by farmers in this area); Sholapur, with  $\delta = 4.0$  weeks, is found to be unsuitable for dry-seeding (a majority of the farmers practice kharif fallow); while at Akola, with  $\delta = 1.9$  weeks, dry-seeding is generally practiced.

In group B1 location 55 differs from 49 and 50 by  $G$ ,  $A$ ,  $C$  and  $\alpha$ . Therefore, this group is further divided into two groups. They are represented by 1111 and 2111. Similarly in B2 location 19 differs from 34 by  $G$ ,  $C$ ,  $D$  and  $G'$ . Hence, they are further divided into two groups and are represented by 3211 and 3212.

C1 is similar to 1112. In C2, location 33 differs from locations 45 and 58 by  $G$  and  $G'$  while location 60 differs from these locations by  $G$ . Because of this difference, locations 33 and 60 are separated from this

group and added to the appropriate groups where these are quite similar. Locations 45 and 58 are represented in group 2211 while 60 is represented in 1233 along with location 59 from E3 and 33 is represented in 2222 along with 46 from C5 and 71 from C6. Similarly in C3, location 53 is represented by 2112 while locations 36 and 37 along with 39 from S7 are represented by 2241. Location 53 differs from 36 and 37 by G, C and A. C4 is represented by 2231. In this group, location 48 from S7 is also added. Locations 41 and 47 from S7 are grouped under 2332 and location 51 along with location 52 and 54 from C5 are represented by 2221 - the difference is not high in these three (2221, 2231 and 2232) groups. C6 is represented by 2222 along with 33 from C2 and 46 from C5.

Group D1 is represented by 4311. At location 78, in group D2, dry-seeding is risky ( $\delta = 3.9$  weeks) while at location 92 (group D2) it is feasible ( $\delta = 2.7$  weeks). Consequently location 78 is added to 99 from group H9 and is represented by 5211, while 92, together with 74, 76 and 109 from H1, 91 and 120 from H2, and 86 from H8 are represented by 5312. All these differences are mainly due to the differences in  $\delta$ .

Location 56, from group E1, is represented by 1332, while location 62, from group E1, together with location 64, from group E5, is represented by 1231. At 56, dry-seeding is feasible, while at 62, it is risky. Groups E6, E7, and E8 are represented by 1212, 1211 and 1331, respectively. Groups E2 and E4 are represented by 1232. Groups E3 and E5 are represented by 1233 and 1231, respectively, while location 60 from group C2 is added to the former, and location 64, from group E1, to the latter.

Groups F1, F2 and F8 are represented by 1511, 1411 and 2412, respectively. Locations 72 and 94, from group F3, are represented by 2411 and 2511, respectively. At 94, dry-seeding is highly successful, while at 72 it is only moderately successful. Locations 77, 142 and 145, from group F5, are represented by 2321 together with 143 from F7. Locations 170 and 171, from group F4, together with locations 146 and 188, from group F5, location 176, from group S11, and locations 28, 35 and 43, from group S6, are represented by 2332. In classes 2321 and 2331 A forms the basic difference: it is  $< 20\%$  in the latter. This characteristic is very important in defining the level of inputs into

agriculture<sup>1</sup>. Locations 137, 139 and 165, from group F5, are represented by 2421. Location 179, from group F5, is added to location 38, from group S6, and are then represented by 2423. Location 160 (group F5) together with location 31 (group S5), 32 (group S6), 169 (group S11), 133 and 149 (group S13) and 134 and 187 (group S15) are all represented by 3311. Locations 89 and 144 from group F6, together with location 40 from group S8, are represented by 2331. Locations 158 and 166, and 140 and 141, from group F7, are represented by 2311 and 2312, respectively. The majority of these differences are mainly associated with the level of dry-seeding feasibility (these are primarily seen in groups prefixed by S).

Locations 119 and 130 (group H2) together with locations 126 (group H6), 103 (group S17) and 113 (group S21) are represented by 4322. Group H3, together with locations 106 (group H5), 147 (group H10), 184 (group H11) and 87 (group S21) are represented by 5411. Location 81 (group H4) together with location 83 (group H6), and 125 (group H8) are represented by 5311. Location 112 (group H5) is represented by 5511. Location 150 (group H7) together with locations 151 and 156 (group S17) and 129 (group S21) are represented by 3421. Locations 162 and 189 (group H11) are represented by 5521. These differences are mainly associated with  $\delta$ .

The 4 locations in S1 differ, both with regard to  $\delta$ , which defines the level of dry-seeding, and W, which defines the level of water-logging hazard. Therefore, the 4 locations in group S1 are separated and grouped with more appropriate agronomically-relevant locations. Location 15 (group S1) is represented by 3432, location 7 (group S1) is added to 8 (group S2) and are represented by 3521, and location 20 (group S1) is represented by <sup>35 //</sup>3522. For arid and sub-humid groups the sequences observed in earlier sections are also used in this section (Table 6-4), because they represent relevant agronomic groups.

In view of the above discussion, the appropriate groups for classification of the SAT into relevant agronomic zones appear to be those presented in Table 6-4. Detailed discussion of the agronomic relevance of these groups now follows.

---

<sup>1</sup> as the risk decreases one can go to higher inputs and with increasing risk one must go to lower inputs

## 6.7 CLASSIFICATION OF ZONES IN INDIA, SENEGAL AND UPPER VOLTA

### 6.7.1 Arid zone

The classification shown in Table 6-4 indicates that the arid zone is characterized by an available effective rainy period < 5 weeks, a c.v. of 111%-204%, a risk level of 61%-81%, and fewer wet spells than dry spells. The seven arid locations are arranged into four sub-zones and sub-zone 3 is further divided into two groups (classes 0311 and 0321) based on the values of C and A. In sub-zone 2 (class 0211) it is very risky to grow a food crop. In other sub-zones (classes 0311, 0321, 0411 and 0511) in 30%-40% of the years, a 75-day pearl millet is successful. This is also evident from soil-water balance simulation results (Chapter 5) for Jodhpur (class 0321). In general, this zone is <sup>better suited</sup> ~~highly suitable~~ for fodder production.

### 6.7.2 Semi-arid zone

The semi-arid tropics are divided into five zones based on the average available effective rainy period, and these are further divided into five sub-zones each based on the level of dependability expressed by the standard deviation of the commencement time of sowing rains. However, some of these sub-zones do not occur in the present data set: namely sub-zone 1 in zones 3 and 5, and sub-zones 1 and 2 in zone 4. In all, there are 21 sub-zones in the present data set. Whenever necessary, these are further divided into groups and sub-groups based on other agroclimatic variables. The results are discussed below, at sub-zone level, according to rainfall dependability. In all, there are 60 sub-groups in the present data.

#### 6.7.2.1 Highly undependable zone [HU]

Only two zones are present in this sub-zone. Dry seeding is not feasible in this sub-zone. Hence, dry-land agriculture is highly undependable. Identification of the proper sowing time is critical for food crop production. Large S and C suggest that in years of early rains, if sufficient rains occur (to fill to field capacity the top few cms of soil), a short duration kharif crop followed by a late kharif crop can be grown. This practice not only reduces soil erosion, it utilizes the initial rains better. In years of late rains, the late kharif practice is better. The main crop season is late kharif and the appropriate time of sowing is represented by S.

**Zone 1:** In this zone the risk is 38%–50%, there are fewer wet spells than dry spells and, also, wet spells are less than 4 weeks, with an s.d. of < 2.5 weeks. The c.v. of the effective rainy period is 80%–100%. There are two sub-groups in this zone (classes 1111 and 1112). In this zone a 60 to 75-day cowpea (or horsegram) followed by a pearl millet of 75 to 90-day with good, early rains, or a 75 to 90-day pearl millet with late rains, can be grown. Here, pearl millet, sorghum, maize, etc., can relate to the level of drought conditions at a location. Pearl millet can give better yields even under stress conditions, and next in order are sorghum and maize. Similarly, horsegram and cowpea, castor and pigeonpea, chickpea and wheat, etc., can relate to dry to wet conditions<sup>2</sup>.

**Zone 2:** In this zone the risk of aridity is < 30%, and, also, C is < 80%, wet spells are longer than 3 weeks with an s.d. of more than 2 weeks, and there are fewer wet spells than dry spells. There are two sub-groups (classes 2111 and 2112) in this zone. The above cropping pattern can be followed with a pearl millet of 90–100 days. Runoff recycling is beneficial in this zone.

#### 6.7.2.2 Undependable zone [UD]

Dry seeding is risky in this sub-zone. Crop production depends highly upon the proper identification of the sowing time.

**Zone 1:** This zone is characterized by a high risk of aridity of 40%–60%. These areas are prone to major drought in the SAT of India. In this zone C is > 80%. The high C is not only associated with the onset time of sowing rains, as in the sub-zone above, but also upon the cessation time of the rains. This zone is divided into two groups based on the level of risk (A). Group 1 is further divided into two sub-groups (classes 1211 and 1212) based on the dry spells, and group 2 is divided

---

<sup>2</sup>Note: These conclusions are only valid when the rainfall is associated with one continuous season or two continuous rainy seasons separated by a long dry period. In certain parts of the world it often happens that after the main rainy season rains, undependable second rainy season rains occur. However, the second rainy season rains alone may not permit the raising of crops. However, these rains have both good and bad effects. In areas where the occurrence of second season rains (in this case there will be no significant break between the termination of main rainy season rains and the second rainy season rains) is significant then crops that are sensitive to rains at physiological maturity, such as sorghum, pearl millet, tobacco, cotton, etc., are less suitable. Therefore, these crops need to be replaced by suitable crops which are less sensitive to rains at physiological maturity, such as maize, cassava, beans, kenaf etc. The remarks are even valid for other sub-zones and zones under such conditions.

into three sub-groups (classes 1231, 1232 and 1233) based on A, C and W. In this zone, kharif followed rabi sorghum is highly successful in the vertisols; while for alfisols, with good, early rains, a long duration castor or an intercrop of pearl millet/castor is successful, alternatively, either a pearl millet or a horsegram, with late rains. This pattern is also evident from the soil-water balance simulation results (hereafter these results refer to those presented in Chapter 5) for Anantapur (class 1231) and the crop performance results for Bellary (class 1211), Anantapur (class 1231) and Bijapur (class 1231). The soil-water balance simulation results also suggest that there is good scope for runoff recycling in the alfisols, which can reduce the risk level.

**Zone 2:** In this zone C is  $< 100\%$ , and  $\alpha$  and  $\beta$  are generally  $> 2$  weeks. This zone is divided into four groups based on A. Groups 2-4 are further divided into two sub-groups each based on W, D and  $\beta$ . They are represented by classes 2211, 2221, 2222, 2231, 2232, 2241 and 2242. In years of early rains, a short duration pulse (60-75-day), such as cowpea or horsegram, followed by a 90-day cereal crop [pearl millet or finger millet, according to wet and dry spells in the alfisols, for example, finger millet at Bangalore (class 2222) and pearl millet at Sholapur (class 2232), sorghum in the vertisols]. In years with late rains, a late kharif crop [pearl millet or finger millet in the alfisols and sorghum in the vertisols] of 90 days duration is feasible. In the vertisols, a sorghum or pearl millet/pigeonpea intercrop is also successful. Water-logging is a problem in the vertisols, and it needs proper land management. Some of these observations can also be seen from the soil-water balance simulation results for Bangalore (class 2222) and Sholapur (class 2232), under alfisols and vertisols, respectively.

**Zone 3:** With C  $< 70\%$ , this zone is divided into two groups based on C. Group 1 is further divided into two sub-groups (classes 3211 and 3212) based on D. Group 2 is represented by class 3221. In this zone, intercropping is successful in years of late rains and double cropping is successful in the years of good, early rains. In classes 3211 and 3212 pearl millet-based cropping is most suitable, while in class 3221 a sorghum-based cropping pattern is better. Water-logging is a problem, particularly in class 3221 and runoff recycling is beneficial in this zone. Soil management is also important in class 3221.

**Zone 4:** C is very low, wet spells are longer than 8 weeks and dry



spells are longer than 7 weeks, and there are more wet spells than dry spells. In this zone, only one sub-group (class 5211) is present. This zone represents the typical west African undependable double-cropping zone. A sorghum-based cropping pattern with late rains, or a maize-based cropping pattern with early rains, is successful, with both sorghum and maize being long duration crops. The double-cropping is of sequential pattern.

#### 6.7.2.3 Dependable zone [DP]

In this <sup>sub-</sup>zone, dry-seeding is feasible with careful planning. There are five zones.

**Zone 1:** C is > 80% with a risk > 40%. There are fewer wet spells than dry spells. This zone is divided into two groups based on D and  $\alpha$  (classes 1331 and 1332). This zone is suitable for single cropping. In class 1331, pearl millet-based cropping (as wet spells are considerably fewer than dry spells) and in class 1332 sorghum-based cropping are successful with early rains. Pearl millet-based cropping is also successful with late rains in both groups, the crop varieties being of short duration (< 90 days).

**Zone 2:** C varies between 36%–82% with a risk of 7%–38%. This zone is divided into four groups. C is > 60% in group 1. This is further divided into two sub-groups (classes 2311 and 2312) based on C. In group 2 (class 2321) A is 20%. Group 3 is further divided into two sub-groups (classes 2331 and 2332) based on wet spells. Except in group 4 (class 2341) there are fewer wet spells than dry spells in this zone. In class 2341, a sorghum/pigeonpea intercrop with late rains, or maize + chickpea double cropping with early rains, is successful. Harvesting of a kharif crop may pose problems. In the remaining groups, with early rains, intercropping of sorghum or pearl millet/pigeonpea, or a single cropping of sorghum with late rains, is successful in alfisols. For vertisols, with early rains, double cropping (sorghum + chickpea), or intercropping (sorghum/pigeonpea) with late rains, is successful. This is evident from the soil-water balance simulation results from Hyderabad (class 2332) under alfisols and vertisols. In class 2341, with late rains in alfisols, finger millet can also be grown. Water-logging may pose a problem in this zone. Again, proper management of the soil is necessary. Runoff recycling is important in both alfisols and vertisols to increase the productivity in this zone.

**Zone 3:** This is a double cropping zone. Water-logging is a problem, and soil management is essential for successful harvesting of the kharif crop. This zone is further divided into three groups: (i) class 3311 ( $W < 5$  weeks and  $W < D$ ) supporting sorghum/cotton intercropping in alfisols and sorghum + chickpea double cropping in vertisols; (ii) class 3321 ( $W > 5$  weeks and  $W < D$ ) supporting maize + chickpea with early rains, or sorghum + chickpea with late rains in vertisols, sorghum + chickpea double cropping with early rains, or sorghum or pearl millet/pigeonpea intercropping with late rains in alfisols; and (iii) classes 3331 and 3332 ( $W > 6$  weeks and  $W > D$ ) supporting paddy-rice-based double cropping with early rains and maize-based double cropping with late rains in vertisols, and finger millet-based double cropping in alfisols.

**Zone 4:** Wet and dry spells are nearly equal and dry spells are long. This zone supports intercropping, but the crop varieties must be of long duration. This zone is divided into two groups based on the duration of dry spells. Group 2 is further divided into two sub-groups based on the duration of wet spells (classes 4321 and 4322). In group 1 (class 4311), sorghum/cotton (120/200 days) with late rains or maize/cotton intercropping with early rains, are the most suitable, and in group 2 (classes 4321 and 4322), maize/cotton with late rains or paddy/cotton with early rains are suitable.

**Zone 5:** This zone is divided into two sub-groups (classes 5311 and 5312) based on the duration of wet spells. This is a typical intercropping zone, like the above. Here, in class 5311, a sorghum/cotton (120/200 days) intercrop and, in class 5312, a maize/cotton (120/200 days) intercrop are successful.

#### 6.7.2.4 Moderately dependable zone [MD]

Dry-seeding is moderately successful in this <sup>sub-</sup>zone which is further divided into five zones.

**Zone 1:** C is high (86%) and dry spells are considerably longer than wet spells. The risk of aridity is 47% and this zone (class 1411) is suitable for a single pearl millet crop of 90 days duration.

**Zone 2:** This zone is sub-divided into two groups based on A and C. Group 1 is further divided into two sub-groups (classes 2411 and 2412) based on the duration of wet and dry spells. Similarly, group 2 is further divided into three sub-groups (classes 2421, 2422 and 2423). Class 2411 is suitable for a single 90-day pearl millet crop with a risk of

20%-30%, and in the remainder of the sub-groups an intercrop based on sorghum (90/150 days) is suitable. Water-logging may pose a problem for class 2423.

Zone 3: Water-logging is a major problem in this zone which is divided into three groups. Group 1 is further divided into two sub-groups (classes 3411 and 3412) based on C. In class 3411, c.v. (C) of G is  $> 25\%$ , while it is  $< 25\%$  in class 3412. Group 3 is further divided into two sub-groups (classes 3431 and 3432) based on the duration of wet spells. Only one sub-group is present in group 2 (class 3421). In group 1, sorghum/pigeonpea intercropping in alfisols and sorghum-based double cropping in vertisols are suitable. In class 3421, maize-based double cropping is successful. In class 3431, sorghum/pigeonpea intercropping, in alfisols, or sorghum-based double cropping, in vertisols, are suitable. In class 3432, finger millet- or maize-based double cropping is successful in alfisols or vertisols, respectively. In class 3432, paddy-rice-based double cropping is more successful with early rains in vertisols. Harvesting of a kharif crop may pose problems. For class 3431, these observations can be seen from the soil-water balance simulation results of Akola.

Zone 4: This zone is divided into two groups (classes 4411 and 4421) based on wet spells. This is a major double cropping zone with moderate to severe water-logging problems. Therefore, proper management of the soil is critical. For classes 4411 and 4421, sorghum- and maize-based cropping systems, respectively, are feasible.

Zone 5: Wet spells are longer than dry spells and sorghum or maize based double cropping is successful using long-duration varieties. There is only one sub-group (class 5411) in this zone.

#### 6.7.2.5 Highly dependable zone [HD]

Dry-seeding is highly successful and, in general, water-logging is a major problem. Therefore, land management is important in this <sup>sub-</sup>zone, which is divided into five zones.

Zone 1: Only one sub-group (class 1511) is present in this zone with  $C > 60\%$ . A single 90-day sorghum crop is successful with a risk of aridity of 30%.

Zone 2: This zone is divided into two groups (classes 2511 and 2521) based on C. Group 1 (class 2511) is suitable for a single pearl millet crop, while group 2 (class 2521) is suitable for a single sorghum crop or sorghum-based intercropping.

**Zone 3:** This zone is divided into two groups based on the duration of wet spells (classes 3511 and 3521). In group 1 (class 3511) either pearl millet- and sorghum-based double crops (with early rains) or intercrops (with late rains) are successful in alfisols and vertisols, respectively. Group 2 (class 3521) is suitable for paddy-rice-based (with good, early rains) or maize-based (with late rains) double crops in vertisols, and in alfisols finger millet-based double cropping is successful. These observations can also be seen from the soil-water balance simulation results of Indore (class 3521). There are major problems in terms of cultural operation and harvesting of the kharif crop in this zone, particularly in class 3521.

**Zone 4:** With  $C < 15\%$ , this zone is divided into 2 sub-groups (classes 4511 and 4512) based on the duration of wet spells. Class 4511 is better suited for long-duration pearl millet-based intercropping or sorghum/cotton intercropping, while class 4512 is more suitable for sorghum or maize/cotton intercropping. Maize-based double cropping is also possible.

[ 5511 and 5521 ]

**Zone 5:** This zone is divided into two groups based on wet spells. In this zone water-logging is a problem. Maize-based double cropping is most suitable in alfisols and in vertisols paddy-rice-based double cropping.

#### 6.7.3 Sub-humid zone

The 16 sub-humid locations are arranged into five sub-zones based on  $\delta$ , however, the first two sub-zones do not occur in the present data. Sub-zone 3 is divided into three groups based on G, W and D (classes 6311, 6321 and 6331). Sub-zone 4 is sub-divided into three groups based on W and D (classes 6411, 6421 and 6431). Sub-zone 5 is further divided into three groups (classes 6511, 6521 and 6531) based on G and W. In all these groups water-logging is a major problem and, also, there are more wet spells than dry spells. These are major paddy-rice- (with early rains or maize with late rains) based double cropping zones in vertisols, and finger millet- or maize-based double cropping zones in alfisols.

#### 6.7.4 General comment

Figures 6-15 and 6-16 present the spatial distribution of different classes over India, and Senegal and Upper Volta. In Senegal and Upper Volta the zones are nearly parallel to lines of latitude (Fig. 6-16), while in India they are much more complex (Fig. 6-15) because, in addition to regional differences in the circulation patterns, local orographic effects are very important. According to Dancette (1978), a 75-day GAM millet (pearl millet) is grown in the Senegal arid zone (zone 0 in Fig. 6-16), but this is successful in 40% of the years. However, this success increases to 90% for zone 2 and to 80% for a 90-day Souna millet (pearl millet). In zone 3 it is 100% successful. At Bambey, in zone 3 (class 3311), the commencement date of effective rainfall was observed to be between 2 and 13 July from 1973 to 1977 (Dancette, 1978), which is in agreement with  $S = \text{week } 29.1$ , confirming the present findings.

The crop sequence in Upper Volta (Stoop & Pattanayak, 1979) is pearl millet in zones 0-2, sorghum or millet in zones 3 and 4; and sorghum and maize in zone 5. Also, (i) pearl millet is grown mainly on the relatively dry soils of the plateau and upper slopes (these are often shallow, gravelly loam soils, 50 cm deep, overlying laterite); (ii) sorghum and maize are grown in the deep, sandy loam soils of the lower slopes and towards the swamps; and (iii) paddy-rice is grown in the swamps after these have been inundated by fresh rains, generally by the middle of July (Stoop & Pattanayak, 1979). At Kamboinse in zone 4 (class 4511), with  $S = \text{week } 24.4$ , Stoop & Pattanayak (1979) reported that by delaying the sowing date beyond June the yield reduction is substantial. In zones higher than 3, sorghum/cowpea or pearl millet/sorghum intercrops or cowpea/maize intercrops, with different dates of maturity, are found to be promising, where sorghum and maize are long duration varieties and cowpea and pearl millet are short duration (harvesting very early) varieties. In zones 0-3, crop combinations that complement each other in some way other than common maturing dates, such as millet/groundnut, are promising.

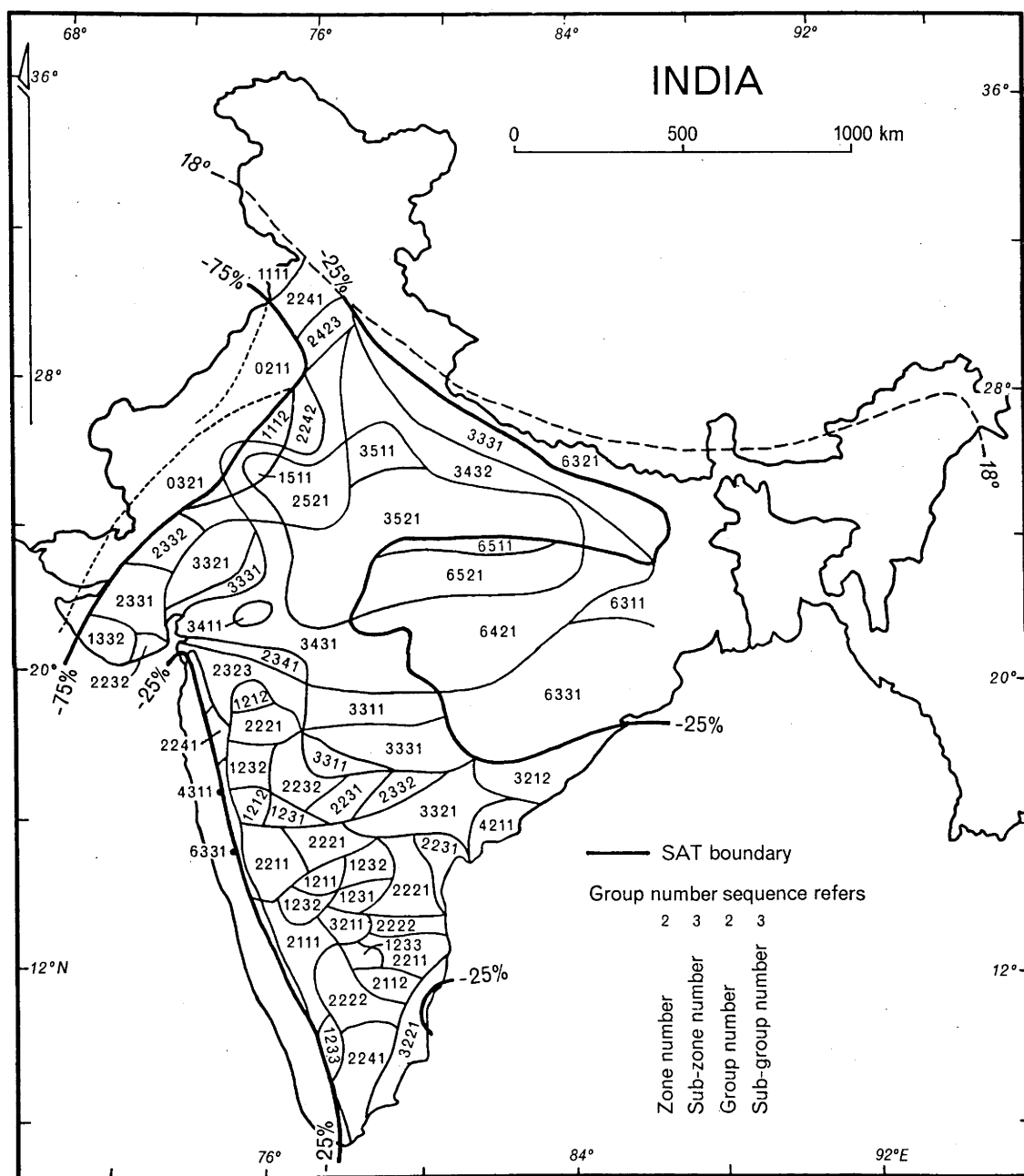


Figure 6-15 : Agroclimatic classification of India.

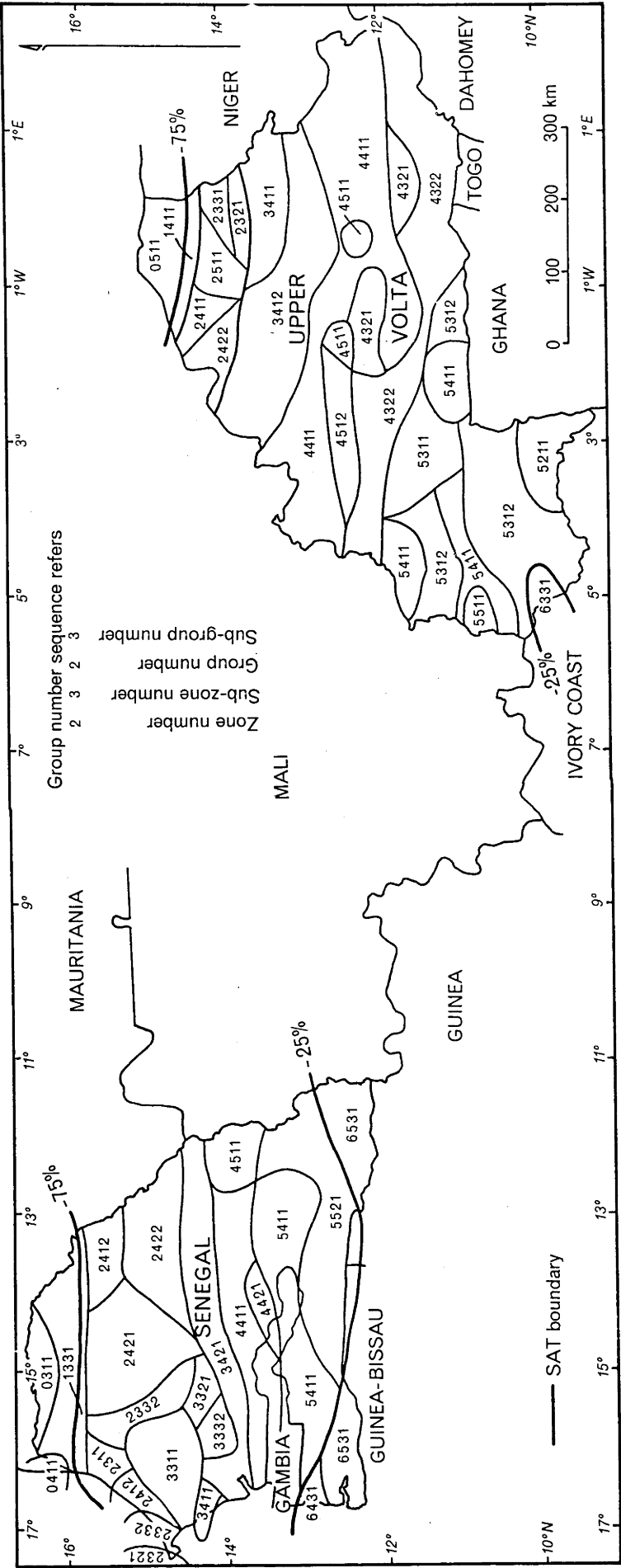


Figure 6-16 : Agroclimatic classification of Senegal and Upper Volta.

## 6.8 SUMMARY

An attempt is made to classify 190 locations from India, Senegal and Upper Volta using numerical taxonomic techniques, such as principal coordinate analysis with ordination, minimum spanning tree (MST) and clustering analysis with three fusion strategies (UPGMA, WPGMA and FB) in conjunction with the Gower metric and the standardized Euclidean metric. Ordination and MST present a continuum of locations in space, but do not adequately define groups. The MST arranged sites according to continents, but the differentiation within the continents was not acceptable. With ordination, even though the first two (or three) coordinates accounted for 75% (or 83%) of the variance in the data matrix, some of the variables showed high and significant correlation using 3-7 coordinates. This inference suggests it is unwise to restrict analysis to a few coordinates only based on variance. In general, the three fusion strategies with two similarity measures separated extreme cases, but misclassifications are most numerous in FB, followed by WPGMA and UPGMA, respectively. Clusters fused under a UPGMA-standardized Euclidean metric combination appear to be the most acceptable, followed by UPGMA-Gower metric and WPGMA-Euclidean metric combinations. However, the UPGMA-Euclidean metric combination using a 7-principal coordinate data matrix has given the most acceptable results. However, these groups are not homogeneous in terms of their capacity to define the level of dependability (particularly at the lower end of the range), which defines the level of dry-seeding feasibility, and wet spells that define water-logging hazards. Consequently, in order to make these groups more relevant to agronomic planning, and to characterize them in terms of agroclimatic variables, (so that new locations can easily be fitted into these groups), they have been adjusted subjectively.

The 190 locations are first arranged into three broad zones, namely arid, semi-arid and sub-humid, according to a modified Thornthwaite approach. The semi-arid locations are divided into five zones based on the available effective rainy period relating to the cropping pattern. As these primary patterns refer to the most stable situation, they are further divided into five sub-zones, each based on the level of dependability characterized by the s.d. of the commencement time of sowing rains. These sub-zones not only indicate necessary modifications to the cropping pattern, but also help in evaluating dry-seeding feasibility. Sub-zones 1



and 2 are not suitable for dry-seeding, and the risk in dry-seeding decreases from sub-zones 3 to 5, suggesting that dry-seeding is highly successful in sub-zone 5. Also, in sub-zone 1 and 2 the cropping pattern is highly unstable and varies according to the commencement time of good, initial rains. The stability of cropping pattern increases from sub-zones 3 to 5. However, these sub-zones are still not homogeneous in terms of crop varieties, i.e., the level of drought tolerance related to the proportion of dry and wet spells within the available effective rainy period. As the proportion of wet/dry spells increases, together with the length of the wet spells, the crop varieties change from pearl millet (crop species that give good yields even under stress) to sorghum, maize, finger millet or paddy-rice (crop species in which yield is substantially affected even for a short period of stress). There are other operational problems, such as water-logging and the availability of field-work days for cultural operations. Therefore, to account for some of these problems, the sub-zones have been divided into groups and sub-groups. Such a sub-division also indirectly accounts for the high variability in the available effective rainy period that facilitate the identification of appropriate crop combinations. Larger numbers of groups or sub-groups in an area are better, in an agronomic sense, than areas with fewer groups or sub-groups.

In all, there are five groupings, with 7 locations, in the arid zone; nine groupings, with 16 locations, in the sub-humid zone; and there are 21 groupings and 60 sub-groupings, with 167 locations, in the semi-arid zone. In the sub-humid zone, one sub-group is common to India and Senegal, but none are common for India and Upper Volta or for Senegal and Upper Volta. There are no common groups in the arid zone. In the semi-arid zone there are 30 sub-groups in India, 19 in Senegal and 20 in Upper Volta. Two sub-groups are common to all three countries, six sub-groups are common to Senegal and Upper Volta, four to India and Senegal and none for India and Upper Volta alone. Zones 4 and 5 are mainly confined to west Africa (except the Belgaum and Samalkot regions in south India that occur in zone 4), similarly sub-zones 1 and 2 are mainly confined to India. The inferences made with reference to Senegal and Upper Volta agree with the experimental findings in terms of the sowing time and probable cropping patterns.

The derived zones and sub-zones of the SAT are straight forward

and make agronomic sense. Given the class structure it is easy to add new locations without further numerical analysis. Such an analysis is now attempted separately in Chapter 7 using an independent data set for tropical Australia.

## CHAPTER 7

### AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS:

#### V. CLASSIFICATION OF TROPICAL AUSTRALIA

##### 7.1 INTRODUCTION

The previous four chapters present a method for the determination of agroclimatic variables and their use in agroclimatic classification. The SAT of India and Senegal and Upper Volta in west Africa were grouped into agronomically relevant homogeneous zones. The objective of the present chapter is to test some of those findings with an independent data set from the SAT of another continent: Australia. Most of northern Australia is used for extensive cattle grazing. The predominant pasture vegetation is tropical grass dominated by the genera *Themeda*, *Heteropogon* or *Sorghum*, occurring mainly in open *Eucalyptus* woodland communities (Moore, 1970; McCown, 1981a). In the past, most climatic classification studies relating to this part of the world have therefore been aimed at understanding the climate as relevant to pastures (Fitzpatrick & Nix, 1970; Reid et al., 1976; McCown, 1981b). But, research over three decades in the Katherine and Darwin region by CSIRO (Australia) and Northern Territory Institutions has demonstrated that dry-land agriculture is feasible; if not always economic. Therefore, using the methods and rules developed in the previous four chapters, an attempt is made to apply these to the SAT of Australia, to identify the regions that may be suitable for dry-land agriculture and to understand their agricultural potential and limitations.

The marked seasonality in rainfall across northern Australia, as in India and west Africa, is linked to movements of the ITCZ (Inter Tropical Convergence Zone). However, rainfall patterns differ significantly over Northern Australia and Cape York one hand and eastern and southern Queensland on the other hand. Southern and eastern Queensland has significant rainfall in winter as well as in summer. Furthermore, trough and tropical cyclonic activity over these regions differ significantly. Also, in

eastern Queensland in particular the climate is modified due to orography. Data from 82 locations in tropical Australia are used in this study. The soil-water balance simulation results for 11 locations are used to characterize some of the groups obtained in the agroclimatic classification. The soil-water balance simulations are made primarily with reference to deep black soils (vertisols), with an assumed water holding capacity of 200 mm, to assess the maximum possible relative productivity level over different parts of tropical Australia<sup>1</sup>. Using data for Katherine (Northern Territory) and Townsville (coastal Queensland), which have about the same mean annual rainfall, the analysis is also carried out for shallow sandy soils of assumed 50 mm capacity and deep sandy soils of assumed 100 mm capacity. To assess the possible success of a rainy season crop, the water requirement estimates for a 100-day crop (as a histogram, for details see Chapter 5) are also used. Crop performance data from Katherine are used in assessing productivity.

## 7.2 DATA AND ANALYSIS

The primary data consist of long-period sequences of observed weekly rainfall for 82 locations in tropical Australia (R. L. McCown, pers. comm.) and long-term mean estimates of weekly U.S. Class "A" pan evaporation (H.A. Nix, pers. comm.). Figure 7-1 presents the locations and Appendix D[D] presents the details on datum period. Unfortunately, the locations are not uniformly distributed over tropical Australia, particularly over southern Queensland, but are the only data available. As in the case of India, high-rainfall stations are not included in this part of the study. This data set primarily covers the semi-arid tropics, similar to those for India and west Africa. In order to understand the relative variation in arid and sub-humid zones, a few locations from these zones are also used in this study. At least the same number of locations are used in the case of tropical Australia as those for India, Senegal and Upper Volta. Consequently, all these countries can be reasonably compared to assess the relative variation of climate as relevant to crop production. The PE values for individual years are derived by adjusting long-term mean values

---

<sup>1</sup>Smith et al. (1983) stated that "The estimated area of vertisols in Queensland is  $50 \times 10^6$  ha (Weston et al., 1981), which is about two-thirds of the Australian total and about one-fifth of the world total area (Hubble, 1972)"

with a rainfall based algorithm (Reddy, 1979a)-- for details see Appendix E. The 9 agroclimatic attributes ( $S$ ,  $\delta$ ,  $G$ ,  $C$ ,  $W$ ,  $\alpha$ ,  $D$ ,  $\beta$  and  $A$ ) are computed for 82 locations using the procedure presented in Chapter 3. Also, the three dissimilarity parameters ( $G'$ ,  $W'$  and  $D'$ ) are derived following the procedure presented in Chapter 4; and soil-water balance parameters for 11 locations are computed following the procedure presented in Chapter 5. Sorghum yield data for 1947-67 and cotton & peanut (Groundnut) for four years are also used for Katherine (H. A. Nix, pers. comm.). Following the procedure presented in Chapter 6 the 82 locations are arranged into agronomically relevant homogeneous groups. These groups are also mapped.

### 7.3 COMPARATIVE STUDY OF AGROCLIMATIC VARIABLES

#### 7.3.1 Spatial distribution of production parameters

The spatial distribution of the nine production parameters are depicted in Figs. 7-2 to 7-10. Also depicted in the figures is the lower boundary (-75% line) of the SAT. However, to avoid the overlap of some of the isolines (for details on the SAT boundary see Fig. 2-6) the upper boundary (-25% line) is not depicted.

The commencement time of sowing rains ( $S$ ) varies between week 48 (first week of December) over Darwin in the Northern Territory and week 6 (middle of February) in Queensland (Fig. 7-2). In general the s.d. of the commencement time of sowing rains ( $\delta$ ) is large (Fig. 7-3) reaching as high as 12 weeks in inland southern Queensland. [Berndt & White (1976) noted a 4-month variation in planting time over years.] These extremely high values are due to the method of computation. In some years, sowing threshold values are not exceeded in the summer, but may be satisfied by following winter rains. In general, the dependability of initial rains is low and hence dry-seeding is unlikely to be a useful strategy in tropical Australia. This unreliability emphasises the importance of identifying the most suitable date for sowing operations.

In the SAT  $G$  varies between 2-16.5 weeks with a c.v. of 20% to 250% (Figs. 7-4 and 7-5). The c.v. of  $G$  ( $C$ ) is similar to  $\delta$  in Fig. 7-3 showing a high variation over southern inland Queensland (Fig. 7-5). This variability is mainly associated with differences in regional circulation patterns. The corresponding values for  $G$  and  $C$  in the SAT of India are 4-16.5 weeks and 15% to 120% (Fig. 4-3).

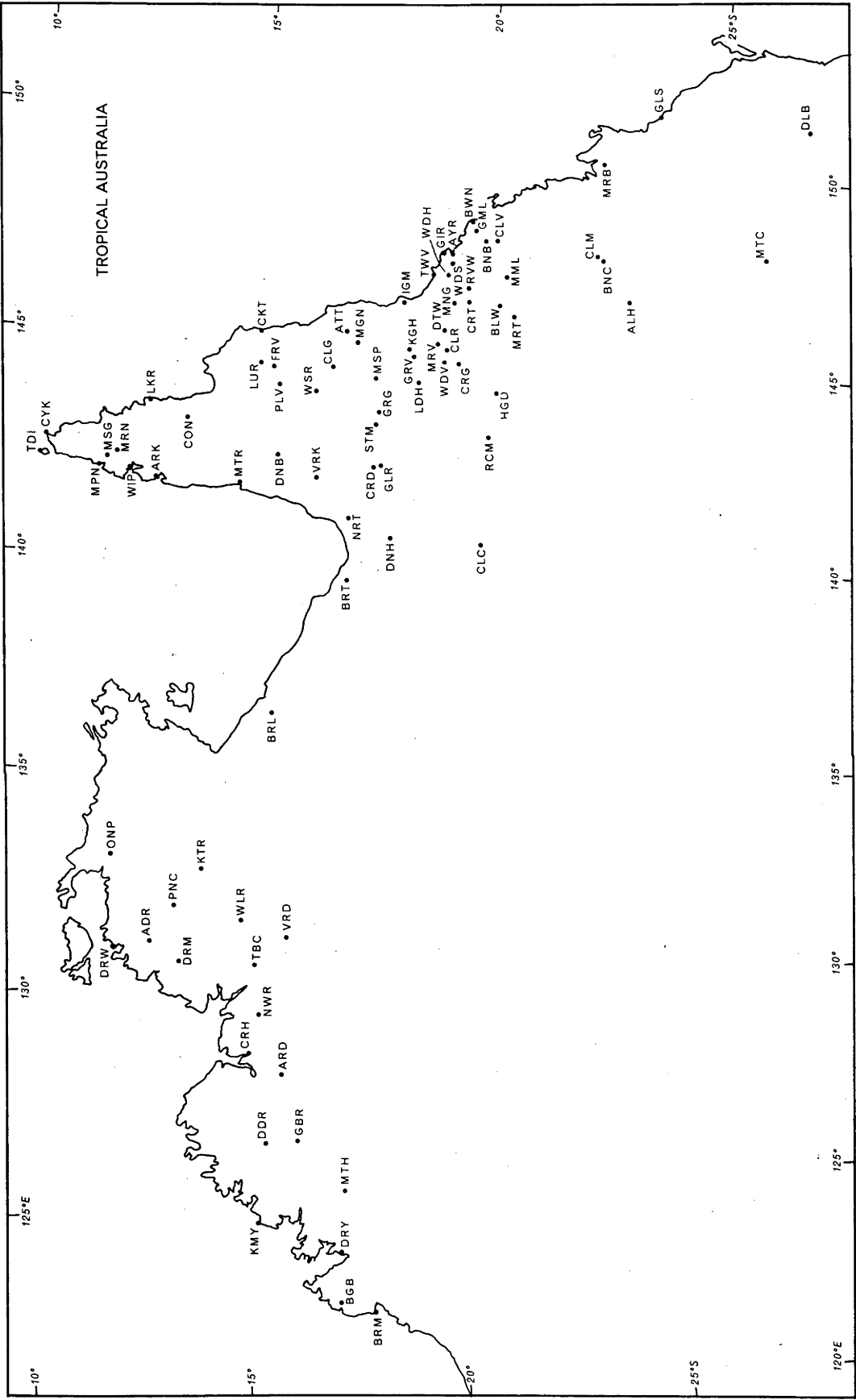


Figure 7-1 : Location of selected stations in tropical Australia.

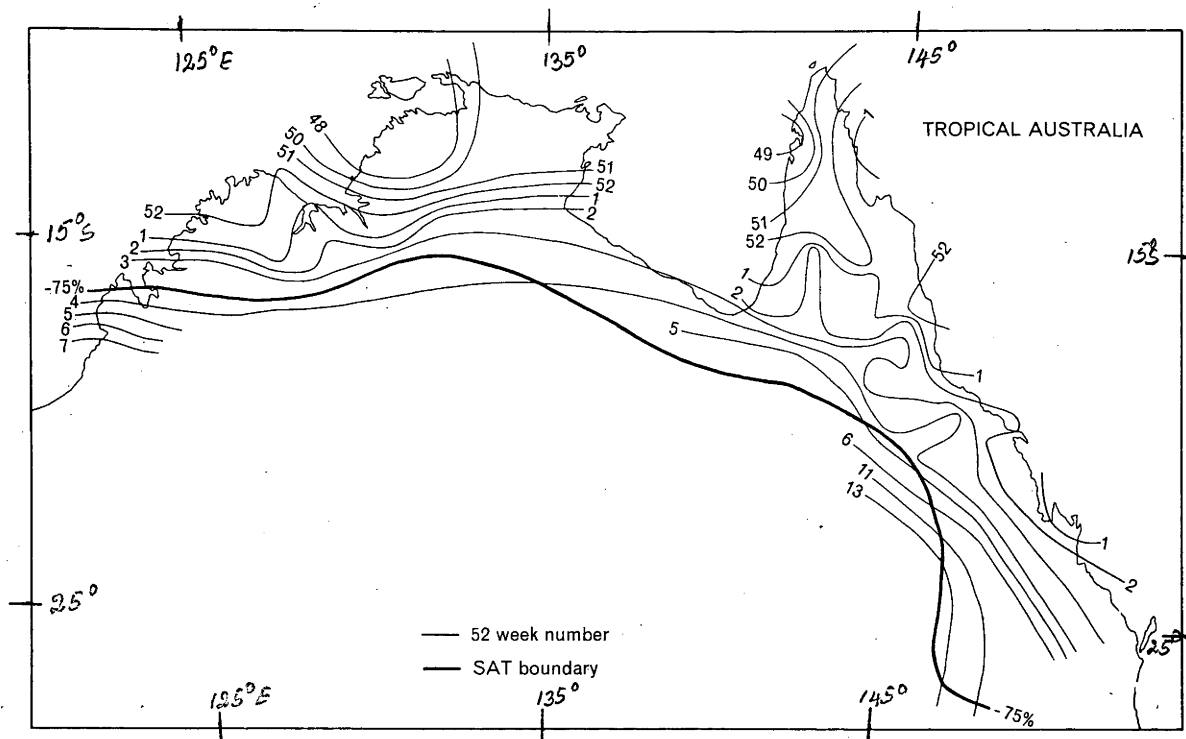


Figure 7-2 : Spatial distribution of the mean week of commencement time of sowing rains ( $\bar{S}$ ), week number.

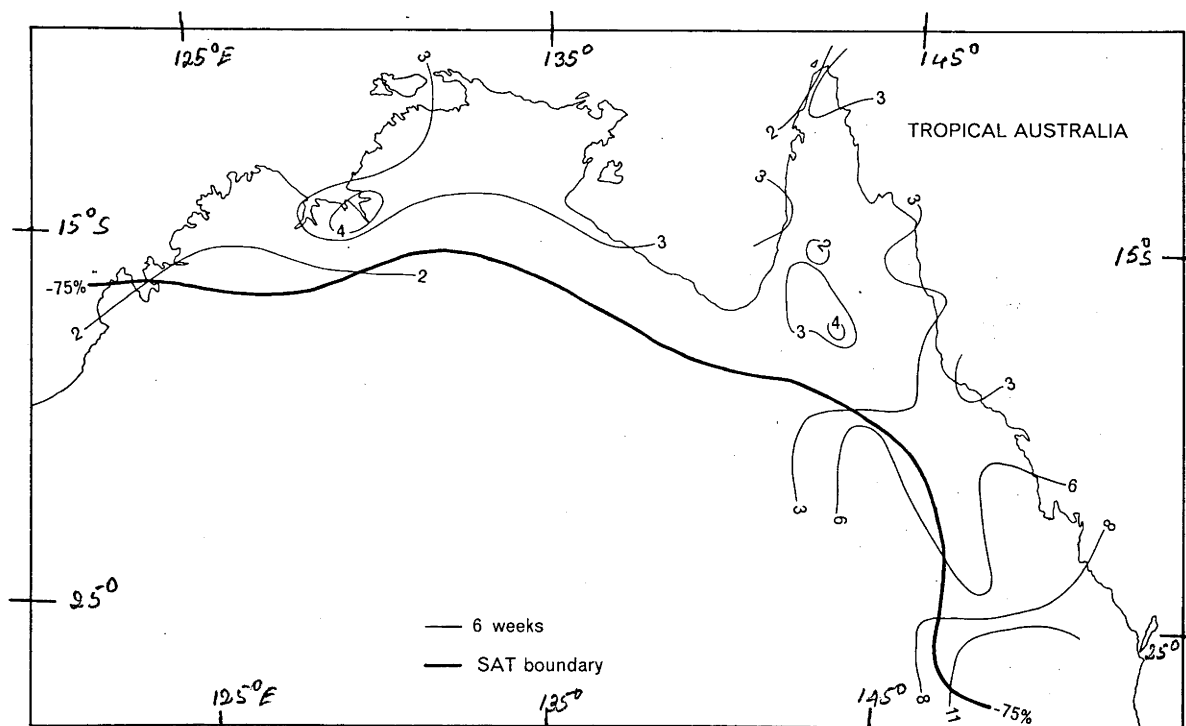


Figure 7-3 : Spatial distribution of the standard deviation of the commencement time of sowing rains ( $\delta$ ), weeks.

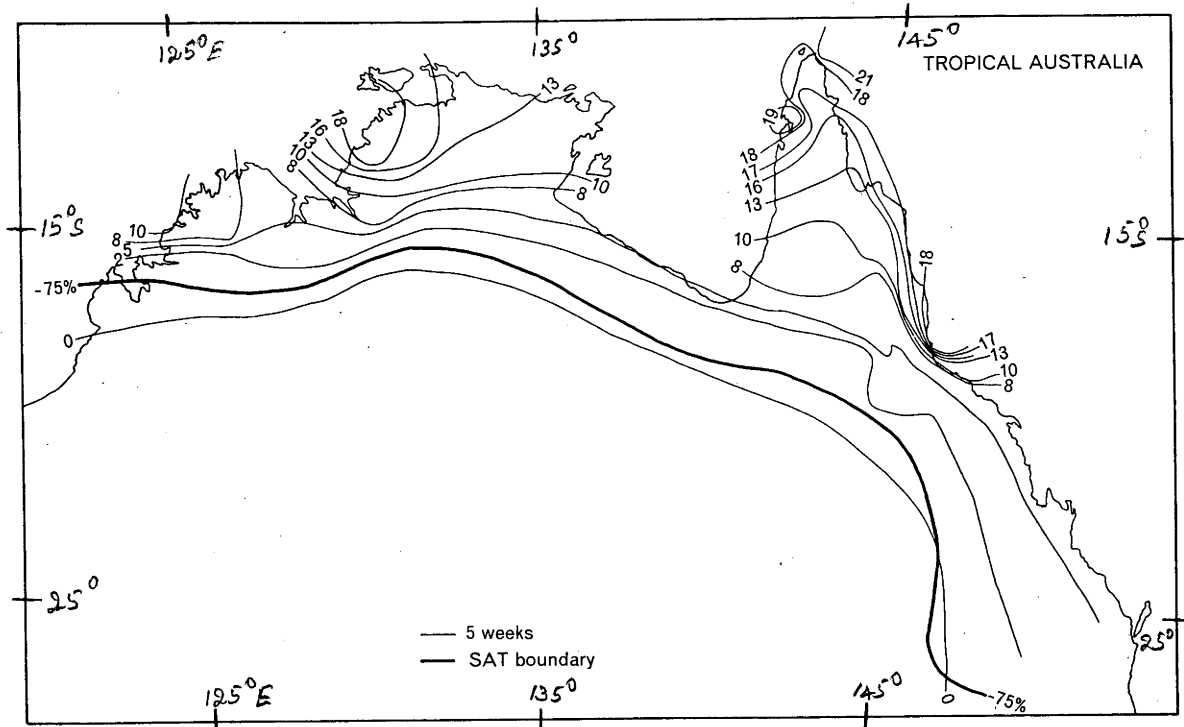


Figure 7-4 : Spatial distribution of the average available effective rainy period (G), weeks.

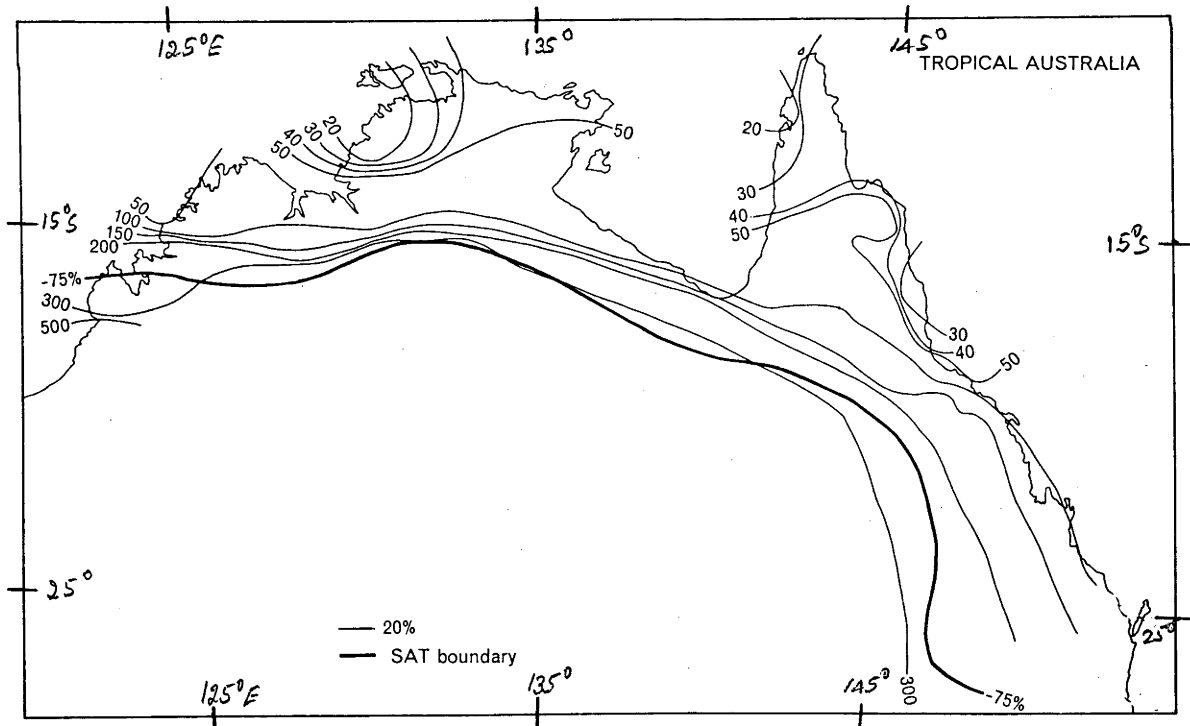


Figure 7-5 : Spatial distribution of the coefficient of variation of the effective rainy period (C), %.



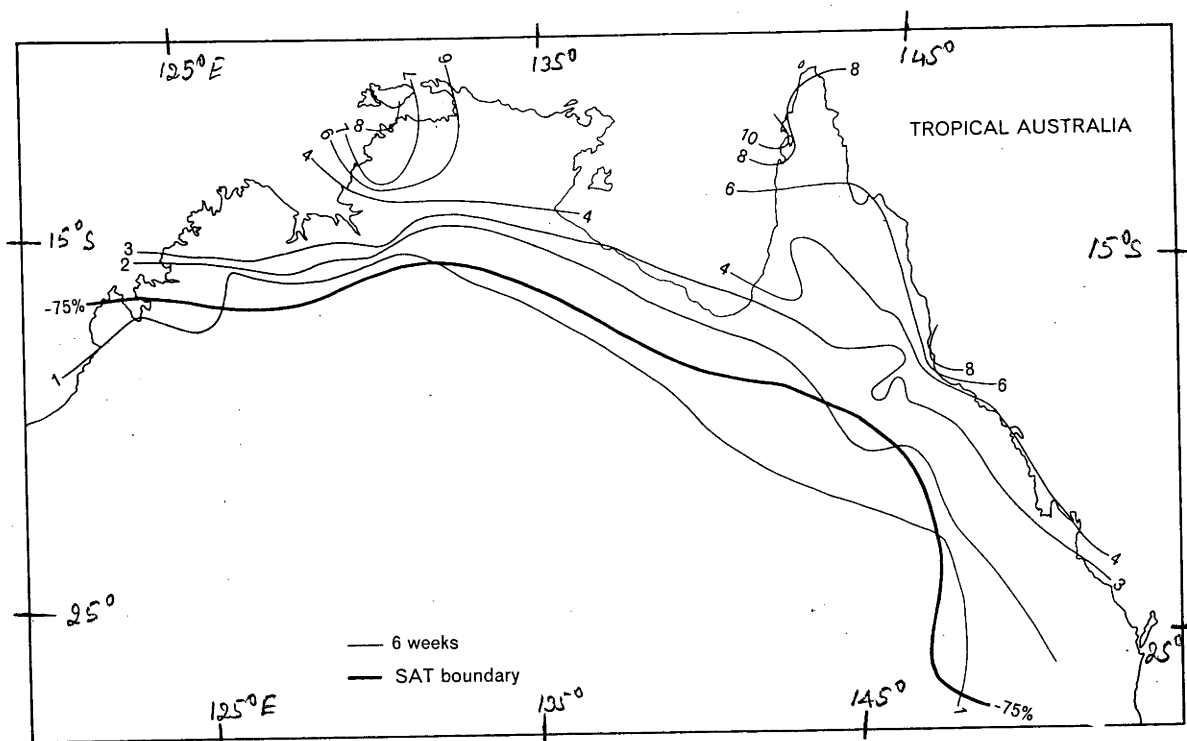


Figure 7-6 : Spatial distribution of the average wet spells within the effective rainy period ( $\bar{W}$ ), weeks.

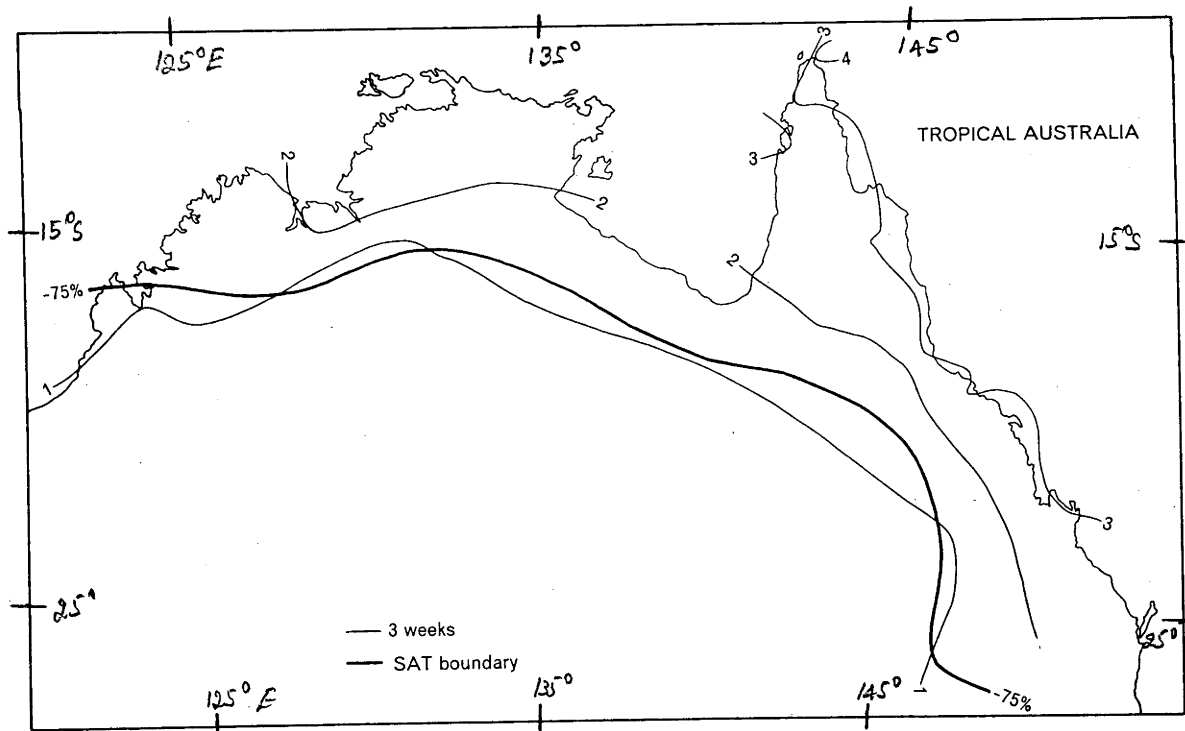


Figure 7-7 : Spatial distribution of the standard deviation of the wet spells ( $\sigma$ ), weeks.

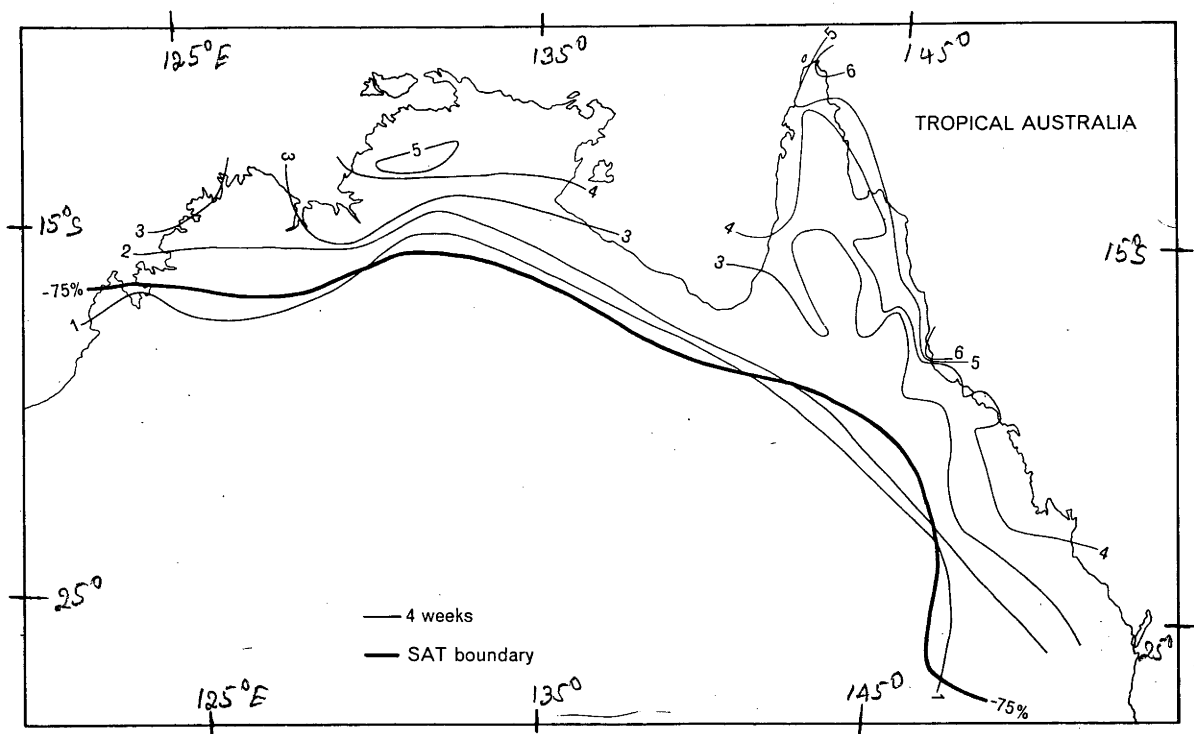


Figure 7-8 : Spatial distribution of the average dry spells within the effective rainy period ( $\bar{D}$ ), weeks.

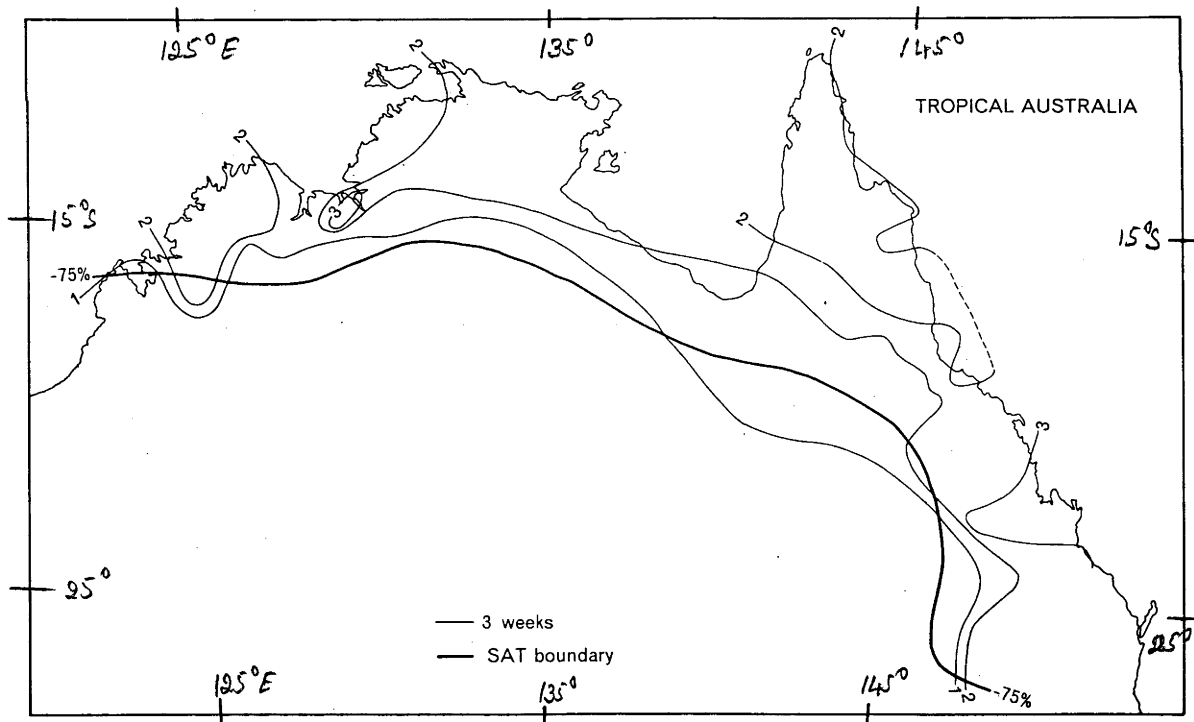


Figure 7-9 : Spatial distribution of the standard deviation of the dry spells ( $\beta$ ), weeks.

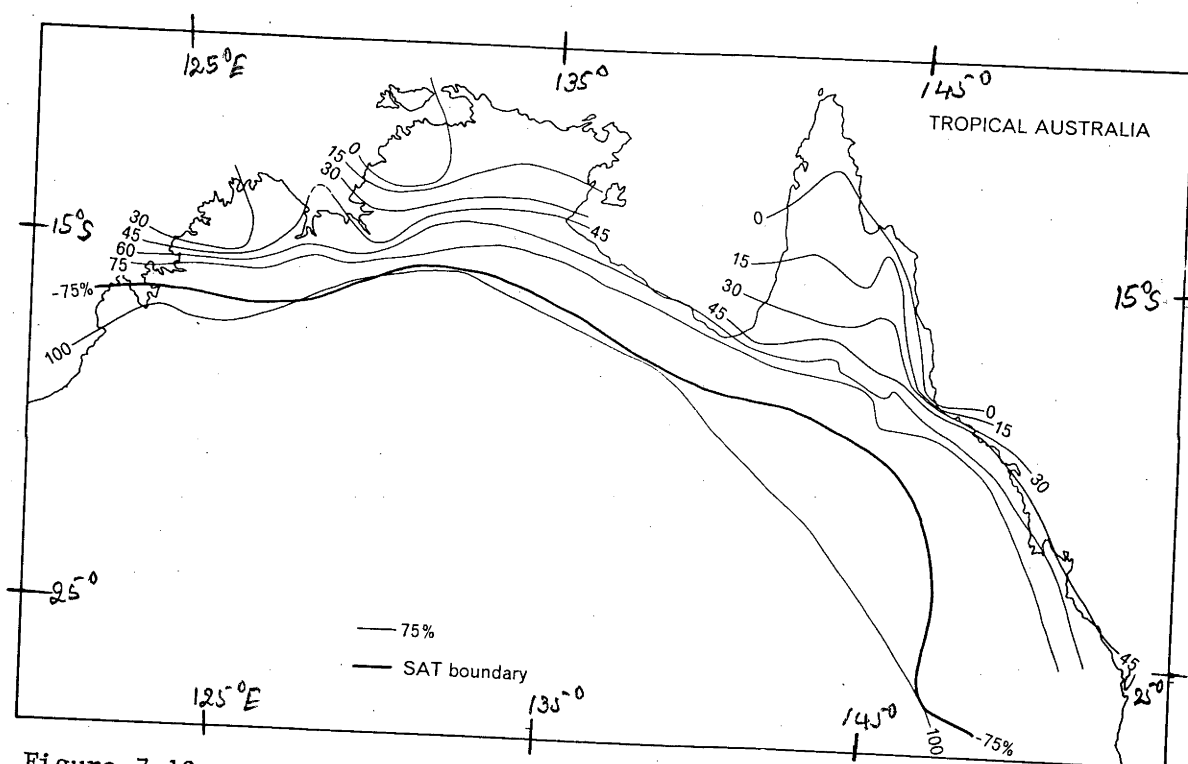


Figure 7-10 : Spatial distribution of the percentage crop failure years ( $G \leq 5$  weeks) (A), %.

Wet spells ( $W$ ) vary from 0 to 10 weeks (Fig. 7-6) with a s.d. ( $\alpha$ ) of 0-4 weeks (Fig. 7-7). The wet spells are lower over south Queensland. Dry spells vary from 0 to 7 weeks (Fig. 7-8) with a s.d. ( $\beta$ ) of 0-3 weeks (Fig. 7-9) with few dry spells over south Queensland. The s.d. of dry spells appears to be smaller than for wet spells (Figs. 7-7 and 7-9). The frequency of wet spells is greater than for dry spells over northern parts of tropical Australia while the reverse is true in south Queensland (Figs. 7-6 and 7-8). The percentage probable crop failure years, the aridity index ( $A$ ), varies between 0% and 100% in the SAT (Fig. 7-10). In the SAT of India  $A$  varies between 0% and 60% (Fig. 4-4).

Some of these results (Figs. 7-2 and 7-4) differ significantly from those obtained by Reid et al. (1976) for growing season estimates and by McCown (1981b) for the commencement and duration of the green season because threshold levels chosen for the initiation of pasture response are less stringent than those chosen for agricultural crops. It is evident from Table 7-1 and Table 4-2 that for the same rainfall the available effective rainy period ( $G$ ) is shorter over the SAT of Australia compared to west Africa and India and the risk is much higher. Towards the drier parts of Australia's SAT the effective rainy period is very low with high risk. In this zone the moisture index ( $I_m$ ) of Reddy & Reddy (1973) that is used in the demarcation of the SAT boundary, also varies between -70% and -75%; i.e., the precipitation meets 25%-30% of PE demand. As the rain falls over a wider period (McCown, 1981b) with high PE hence the effective rainy period for dry-land agriculture is short over these Australian regions.

### 7.3.2 Interrelationships among variables

Figure 7-11 depicts the scatter of  $C$  v.  $G$ ;  $W$  and  $D$  v.  $G$ ;  $W$  v.  $D$  and  $s$  v.  $C$ . The first two [ $C$  v.  $G$  and  $W$  v.  $G$ ] and the fourth [ $W$  v.  $D$ ] present a curvilinear relationship while the third [ $D$  v.  $G$ ] and the fifth [ $s$  v.  $C$ ] present a linear relationship. Except the third [ $D$  v.  $G$ ] these patterns are similar to India and west Africa (Figs. 4-5 to 4-8). The variation of  $C$  v.  $G$  generally follows the pattern of India and west Africa but in order to fit the arid and very dry semi-arid locations the equation is modified (Fig. 7-11). The pattern of  $s$  v.  $C$  follows the west African pattern but the onset of sowing rains shows a higher s.d. ( $s$  is large and more variable) compared to west African situation. Thus, in tropical

Table 7-1 : Climatic attributes for few selected locations in tropical Australia.

			Agroclimatic attributes**					
Station Symbol*	State <sup>#</sup>	@	$\bar{S}+\delta$	$\bar{G}+C$	$\bar{W}+\alpha$	$\bar{D}+\beta$	A	
<u>Low Rainfall</u>								
Broome	BRM	WA	550	5.5+0.5	0.2+550	1.5+1.5	0.5+0.5	100
Derby	DRY	WA	621	4.0+1.0	0.3+230	1.0+1.0	0.5+0.5	100
<u>Medium rainfall</u>								
Mt. Surprise	MSP	Q1D	799	0.3+3.5	6.7+ 90	3.9+2.1	3.8+2.3	44
Burketown	BRT	Q1D	759	4.4+2.5	1.4+200	1.3+1.5	1.1+1.2	100
<u>High rainfall</u>								
Katherine	KTR	NT	952	51.4+3.7	10.6+ 55	4.2+2.8	3.9+2.4	28
Normanton	NRT	Q1D	932	2.0+2.3	6.1+ 80	2.9+1.9	2.0+1.5	44
<u>Very high rainfall</u>								
Oenpelli	ONP	NT	1360	50.1+3.5	14.7+42	5.7+2.9	4.3+2.4	05
Moreton	MRN	Q1D	1362	51.4+2.8	16.1+31	6.4+2.7	3.9+1.7	00

\* Abbreviations as presented in Figure 7-1 & Appendix D(D).

# WA = Western Australia; Q1D = Queensland; NT = Northern Territory

@ Mean annual rainfall, mm.

\*\*  $\delta$ ,  $\bar{G}$ ,  $\bar{W}$ ,  $\alpha$ ,  $\bar{D}$ , &  $\beta$  are in weeks; A & C are in %;  $\bar{S}$  in standard weeks, week number.

Australia both the onset and cessation of effective rains show high variation and are similar to those of some locations in central India. Because of this similarity, the dependability of initial rains, as well as the available effective rainy period, is very low even at high rainfall stations. This trend is particularly evident in the southern parts of the zone studied. The southern and northern parts come under undependable and dependable sub-zones, respectively. This situation necessitates careful planning for the time of sowing, and dry-seeding in vertisols is either just feasible or risky.

At most locations (except southern Queensland) the mean duration of wet spells exceed that of dry spells, a situation significantly different from the patterns in India and west Africa. The curves  $W$  v.  $G$ ; and  $G$  v.  $W$  and  $D$  are closer to India. The proportion of wet spells to the available effective rainy period is nearly equal to the Indian situation and greater than that in the west African situation (Table 7-2); for the corresponding same wet spells the dry spells are fewer in the Australian situation. Dry spells are more than wet spells in the drier parts of India and west Africa.

## 7.4 SOIL WATER BALANCE SIMULATION RESULTS

### 7.4.1 Comparison between northern parts and Queensland

Figures 7-12 and 7-13 present the soil water balance simulation results for Katherine in the Northern Territory and Townsville in Queensland for three levels of available water capacities in the root zone ( $K = 50, 100$  and  $200$  mm) taken to represent shallow sandy soils (aridisols), sandy loam (alfisols), and moderately deep to deep black soils (vertisols) or Alluvial soils. In general terms these represent shallow, medium deep and deep soils, respectively. Both areas have a similar mean annual rainfall. The bottom diagrams present the expected  $AE/E^2$  pattern in 30, 50 and 70% of years and have been constructed from weekly probability data over the period for which climatic data are available. In the crop simulation a fixed planting date of January 10 and a 100-day crop are assumed. In all cases the hatched area represents the crop-water requirement histogram during that 100-day period. The upper curves show

---

<sup>2</sup> $AE$  = actual evapotranspiration and  $E$  open pan evaporation with mesh cover

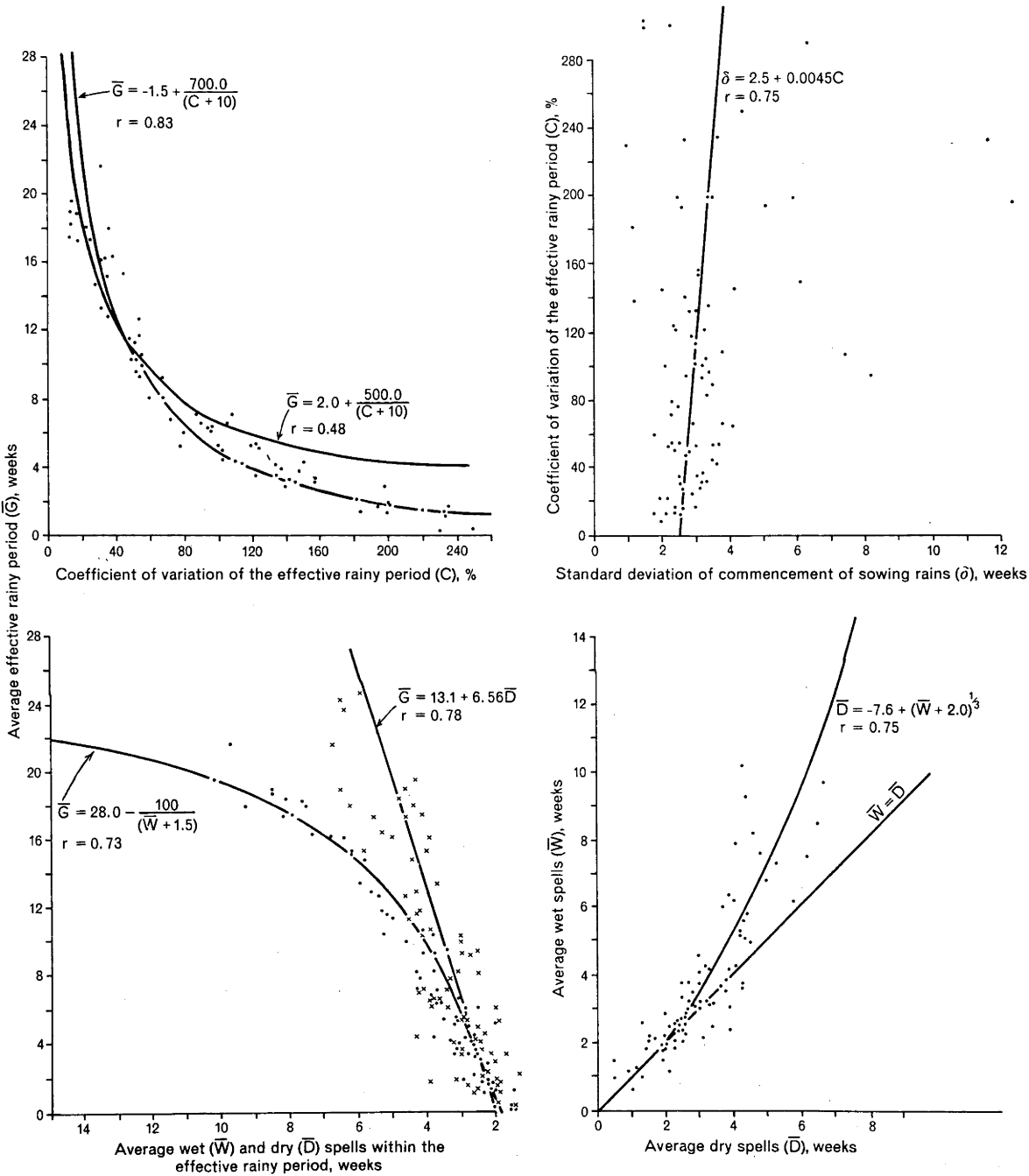


Figure 7-11 : Variation of C versus  $\bar{G}$ ;  $\bar{W}$  and  $\bar{D}$  versus  $\bar{G}$ ;  $\bar{D}$  versus  $\bar{W}$  and  $\delta$  versus C over tropical Australia.

Table 7-2 : Variation of wet and dry spells under different effective rainy periods in different countries (based on Figures 4-6 and 7-11).

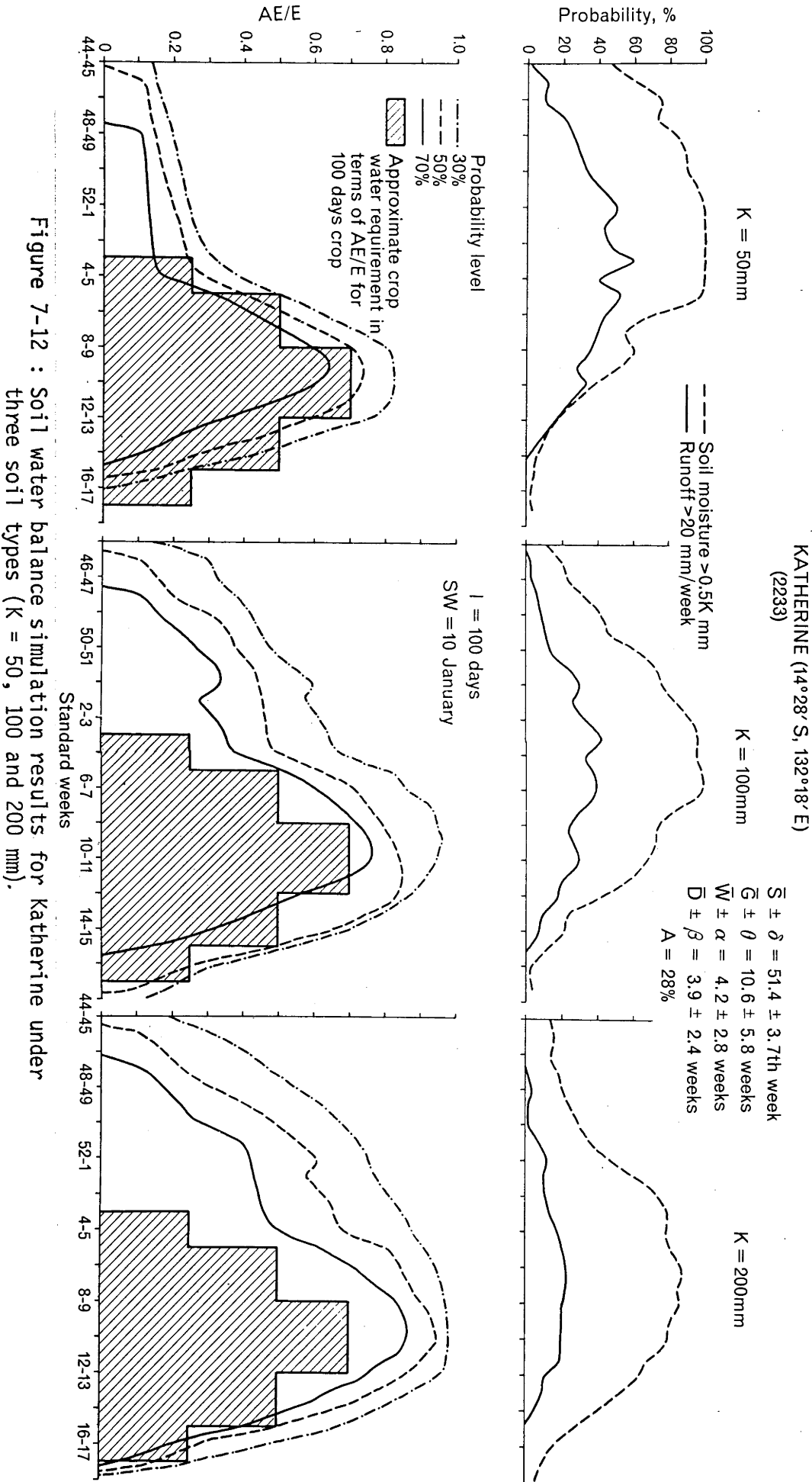
Country	$\bar{G}^*$		13.3		16.0	
	$\bar{W}$	$\bar{D}$	$\bar{W}$	$\bar{D}$	$\bar{W}$	$\bar{D}$
India	4.7	4.7	7.0	5.7		
Senegal	4.0	5.7	5.0	5.7		
Upper Volta	4.0	5.7	5.0	5.7		
Australia	5.2	4.1	7.1	4.8		

\*  $\bar{G}$  = the average effective rainy period, weeks

$\bar{W}$  = the average wet spells within the effective rainy period, weeks

$\bar{D}$  = the average dry spells within the effective rainy period, weeks.





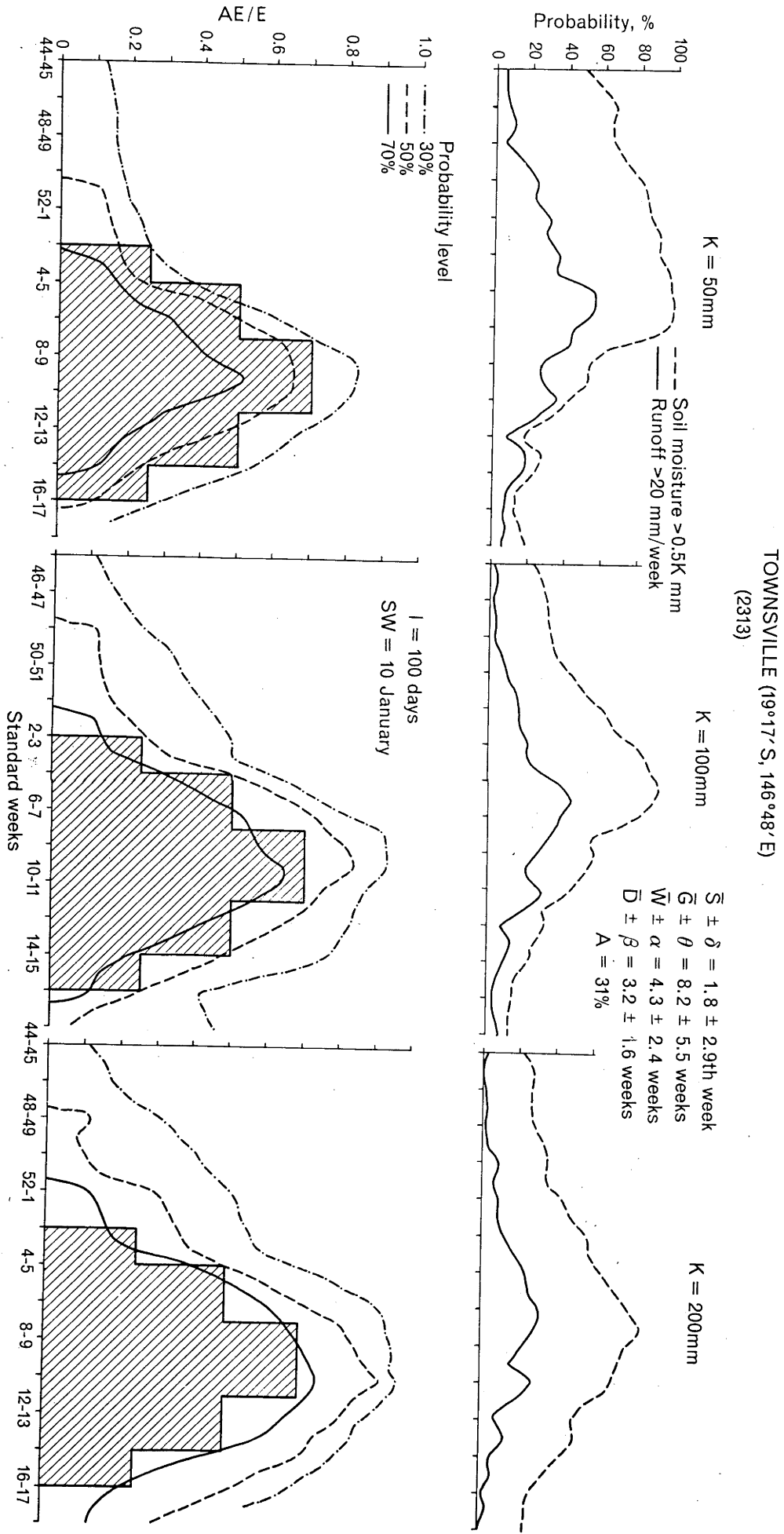


Figure 7-13 : Soil water balance simulation results for Townsville under three soil types (K = 50, 100 and 200 mm).

probabilities of soil water storage exceeding 50% capacity ( $K/2$ ) and runoff exceeding 20 mm/week in any week. The time axis runs from the week 44-45 (i.e., last week of October) to the week 18-19 (i.e., end of April). These details are the same in Figs. 7-15 to 7-18.

At Katherine the probability of soil moisture exceeding 50% capacity is very low after April while at Townsville it is possible once in five years, as Katherine receives no rain in winter<sup>3</sup>. This feature is also seen from AE/E probability curves. At Katherine they reach nearly zero at the end of April whereas at Townsville they are above the zero line even in the case of very sandy soils ( $K = 50$  mm) at the 30% probability level due to winter rainfall. At both places runoff appears to be substantially high, a feature which suggests there is a high potential for recycling the runoff water for increasing productivity in the post-rainy season. This high potential is also evident from wet [W] and dry [D] spells (Figs. 7-12 and 7-13) both of which are of about 4 weeks duration. The low gradient (i.e., probability of getting sufficient moisture for sowing operations is low in any week) at the start of the AE/E curves at Katherine suggests a higher variability than at Townsville. This is also seen from the standard deviation of commencement time of sowing rains (3.7 weeks at Katherine and 2.9 weeks at Townsville). A comparison of the shape of the AE/E pattern and the water requirement histograms suggests that the average planting week (assumed in the computation to be week 2) is appropriate for Townsville, but for Katherine it needs to be somewhat earlier, particularly in deep soils ( $K = 100$  and 200 mm). The estimated average commencement time of sowing rains [S] agrees with this observation since it occurs at the week 1.8 (middle of January) for Townsville and week 51.4 (last week of December) for Katherine.

For both areas the probable success of a single crop on shallow sandy soil is less than 50% while it may be as high as 70% on shallow sandy loams and exceed 70% in the case of moderately deep clays at Katherine. The probability of crop failure is 31% at Townsville and 28% at Katherine. The AE/E pattern suggests that at both locations:

---

<sup>3</sup>These diagrams indicate that the growing season is shorter at Townsville than at Katherine with the same mean annual rainfall because part of the rainfall at Townsville is received in winter (the simulations are based on daily data sets only). These features are also seen in the case of G where it is 8.2±5.5 weeks at Townsville and 10.6±5.8 weeks at Katherine.

- With shallow sandy soils single cropping could be successful with a planting date after the mean week of commencement time of sowing rains [S] when the top 30-cm soil layer is at field capacity:
- With deeper soils, intercropping (100/180 days) could be successful. In the case of moderately deep to deep clay soils planting can be started with the first good rains while in the case of sandy loam soils it is always better to wait until the top-soil attains field capacity with the initial rains. On sandy loam soils at Katherine, groundnut(100-days)/pigeonpea(180-days) intercrop sown after the mean week of commencement time of sowing rains, when the top 30-cm soil is at field capacity with initial rains, can be successfully harvested in 70% of the years.

Experimental crop yields at Katherine Research station (H.A. Nix, pers. comm.) for sorghum grown on deep soils of sandy loams (K = 100 mm) suggests that yield varies with the length of the available effective rainy period [G]-- Fig. 7-14. The yield of sorghum between 1947-67 was  $1710 \pm 830$  kg/ha while the available effective rainy period is  $10.6 \pm 5.8$  weeks. In 1951-52, when the crop completely failed, the available effective rainy period is zero. In some years even though the available effective rainy period is long the yields are low because of the long dry spells during the wet season (large D > 6 weeks). However, surplus water stored in the soil benefited the crop during the succeeding year. Some of these features can be seen in Fig. 7-14. On an average the available effective rainy period is correlated with sorghum grain yields at Katherine (correlation coefficient = 0.55, significant at < 5% level). At Katherine the yields of cotton and groundnut are higher than sorghum (Table 7-3). All these crops represent long duration types, being sown between week 49 and week 3 and harvested some time around the end of May or early June. This suggests that Katherine is more suitable for intercropping than single cropping, but with the option of single cropping in the case of very late rains. The possible intercrops are sorghum/pigeonpea, sorghum/cotton, groundnut/cotton, groundnut/pigeonpea, etc. Sorghum-based intercropping could be successful in deep black soils and groundnut-based cropping could be successful in sandy soils.

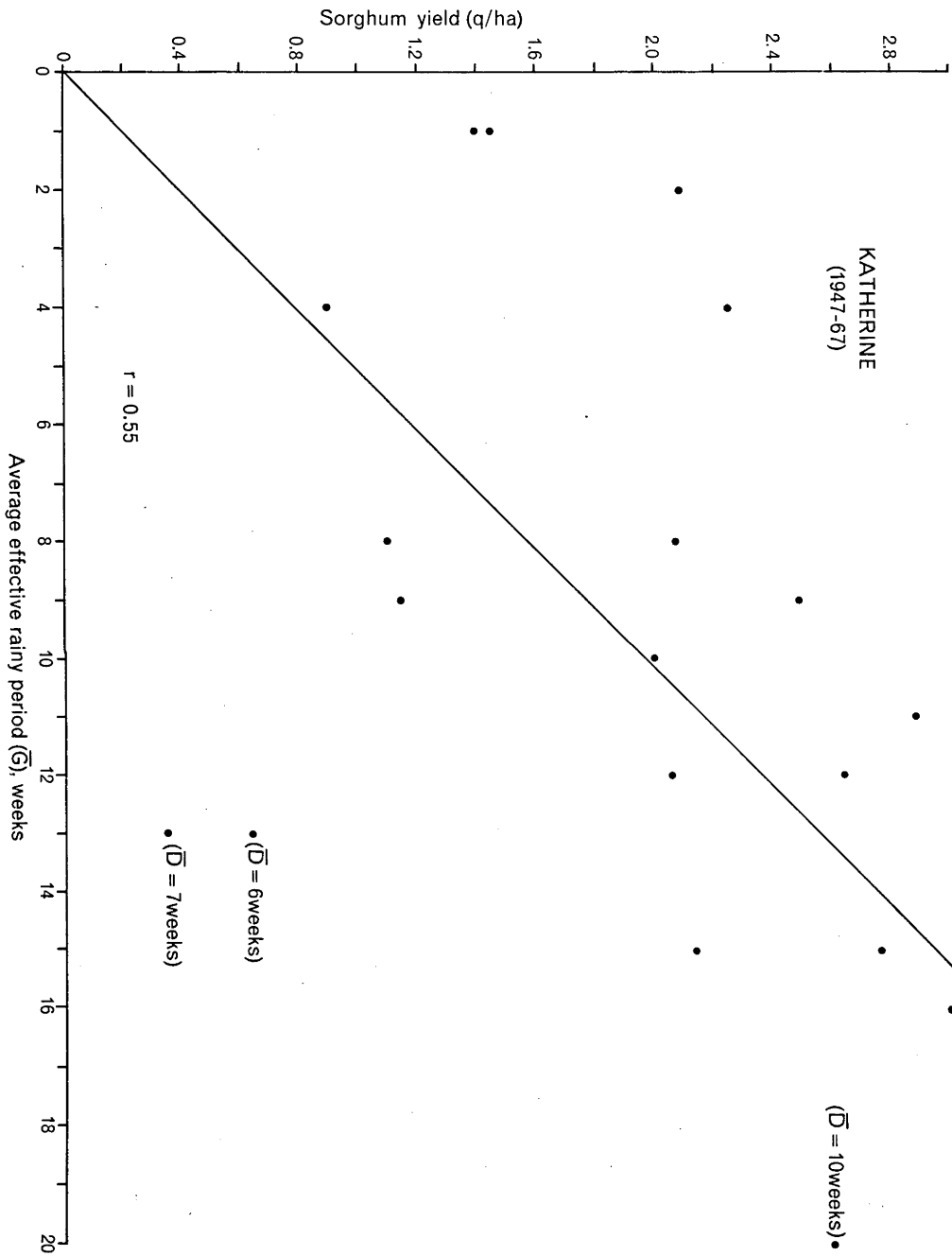


Figure 7-14 : Variation of sorghum yields with the effective rainy period at Katherine.

Table 7-3 : Yield potential at Katherine.

Year	Yield (lbs/acre)		
	Cotton	Groundnut	Sorghum
1954-55	1841	2068	1384
1956-57	1742	1714	1288
1958-59	1950	1450	1380
1959-60	-	2882	1000

Source: H.A. Nix, pers. comm.)

#### 7.4.2 Comparison between arid and semi-arid locations in the Northern Parts

To compare and to characterize the agricultural potential of the northern parts, three locations, one each from arid (Derby), dry semi-arid (Argyle Downs) and wet semi-arid (Pine Creek) are used. Figure 7-15 presents the soil water balance simulation results under deep black soils, which represent the maximum possible moisture regime. Figure 7-12 (Katherine) presents the moderate semi-arid situation. It appears from these diagrams that the most appropriate sowing times are week 48 at Pine Creek, week 2 at Argyle Downs and week 4 at Derby. These dates agree with the S values. At Pine Creek and Argyle Downs the onset of the moisture regime is not sharp, with  $s$  being 3.2 and 2.5 weeks, respectively.

At Pine Creek double crops could be successfully harvested. Even up to 40% of the years have runoff exceeding 20 mm/week. Pine Creek is highly suitable for maize-based double cropping. There is a high possibility that the crop could be successful every year. Because of high variability in the initial rains this area is less suitable for paddy-rice-based double cropping (in some years with good initial rains paddy-rice may be planted). Therefore, irrespective of soil type, maize (100-days) + Chickpea (100-days) sequential cropping could be successfully practiced. The appropriate time for sowing is after week 48 when the top soil is at field capacity.

Argyle Downs is suitable for single cropping; in only about 10% of the years was there runoff. Even in deep black soils single cropping is possibly successful in about 30% of the years. Therefore, irrespective of soil type at Argyle Downs, mixtures of pearl millet (early maturing with less than 90-days) and sorghum (late maturing with more than 90-days) can be sown on any day around week 2 when the top soil is at field capacity (preferable after week 2 in the case of shallow soils).

At Derby the crop may be successful in only 30% of the years, even under deep black soils. Figure 7-15 presents the possibility of getting drought in the middle of February as the soil moisture exceeds 50% capacity only once in three years. Runoff exceeding 20 mm/week is very rare. This means that under moderate soil types the crop would fail in most years. Therefore, this location is more suitable for fodder production than dry-land agriculture.

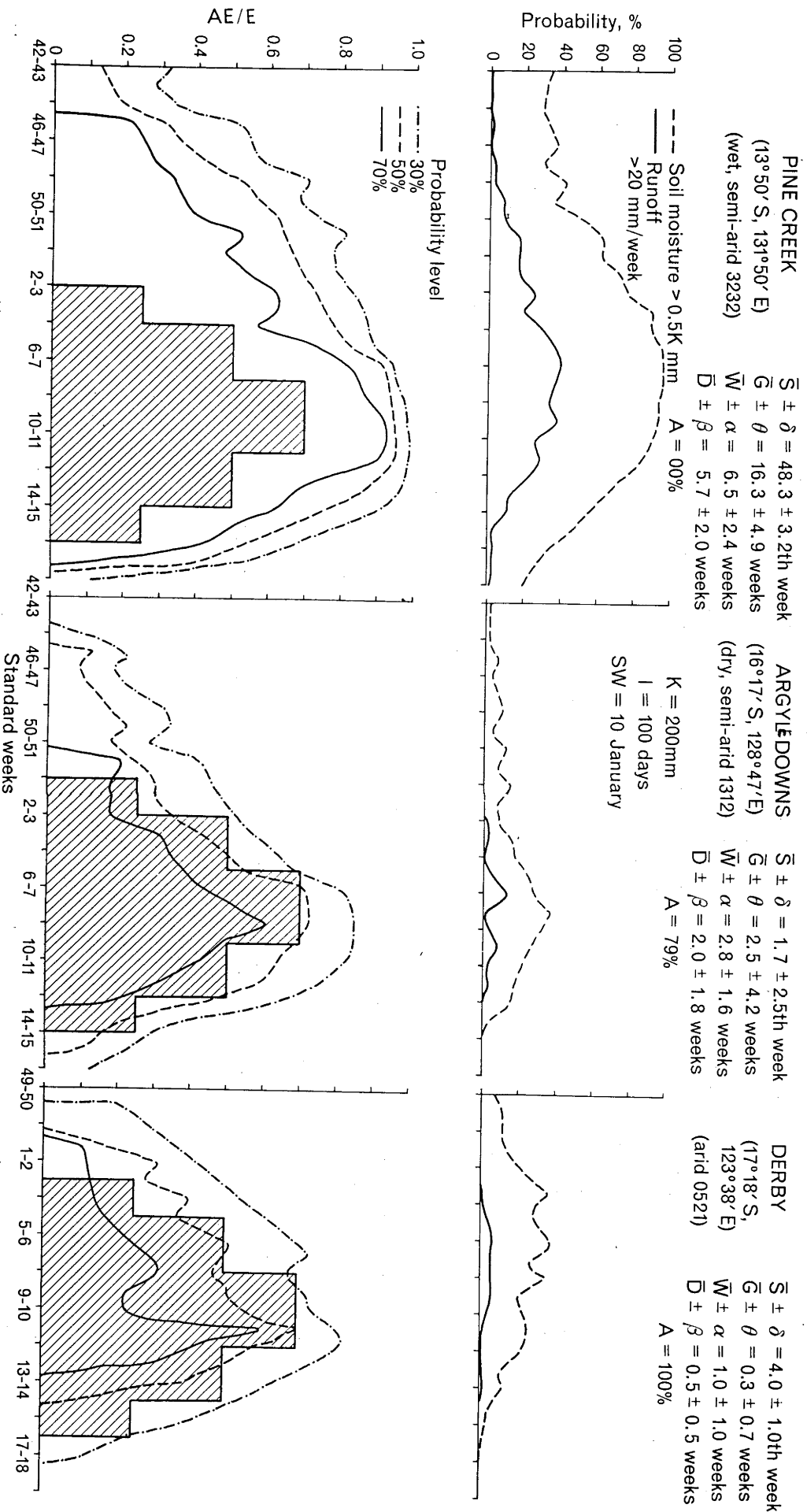


Figure 7-15 : Soil water balance simulation results for Pine Creek, Argyle Downs and Derby under deep black soils (K = 200 mm).



#### 7.4.3 Comparisons between different parts of Queensland

Figures 7-16 to 7-18 depict the soil water balance simulation results over Queensland representing wet and dry situations between 17°17'S to 26°29'S and 143°42'E to 149°58'E. Adopting the procedures described above the following inferences have been made without further reference to maps.

In north Queensland (Fig. 7-16), towards the coast, the moist period extends even into winter (Atherton) while at Mt Surprise it only lasts until April, as in the northern parts. At Atherton, double cropping is feasible with an average planting time around week 1 (week 1 of January) while at Mt Surprise single cropping is feasible in years of late rains while intercropping could be successful in years of very early rains (for example, see AE/E pattern at 30% probability). At Atherton, in 10% of the years runoff was not recorded while it is 50% at Mt Surprise in deep black soils.

Woodstock and Clermont (Fig. 7-17) represent the central parts of Queensland. At Clermont the variability in the initial rains appears to be very high as even under deep black soils the crop would be successful only in 30% of the years in summer. This can be improved by keeping the soil fallow during summer and planting only winter crops on conserved soil moisture<sup>4</sup> similar to Bellary and Bijapur in India<sup>5</sup>. In this situation the appropriate time for planting is after the last week of February or early March, however, the practice would be suitable only for deep soils with high water holding capacity. To reduce the risk, a better practice in the case of sandy soils is fodder production rather than food crop production. At Woodstock, with very early rains, intercropping could be practiced. Sequential cropping is risky as the predicted soil moisture exceeds 50% capacity in winter in less than 20% of the years. In years of late rains only single cropping would be successful. Runoff is observed in 30% of the years at Woodstock while it occurred in 5% of the years at Clermont.

Similar to Clermont, in south Queensland (Fig. 7-18) winter rains are significant but are not usually sufficient to raise a crop without irrigation. Therefore, at Marlborough, unlike Woodstock, with very early

---

<sup>4</sup>This practice is beneficial in sub-zones 1 and 2 of zone 1, as observed in Chapter 5.

<sup>5</sup>This practice is being followed by farmers traditionally on fertile alluvial soils and vertisols with good water holding capacity crops such as wheat. But the yields are low (1034 kg/ha) and highly variable (23%) [Nix & Fitzpatrick, 1969]

ATHERTON (17°17'S, 145°27'E)  
(3312)

Mt SURPRISE (17°51'S, 143°42'E)  
(1235)

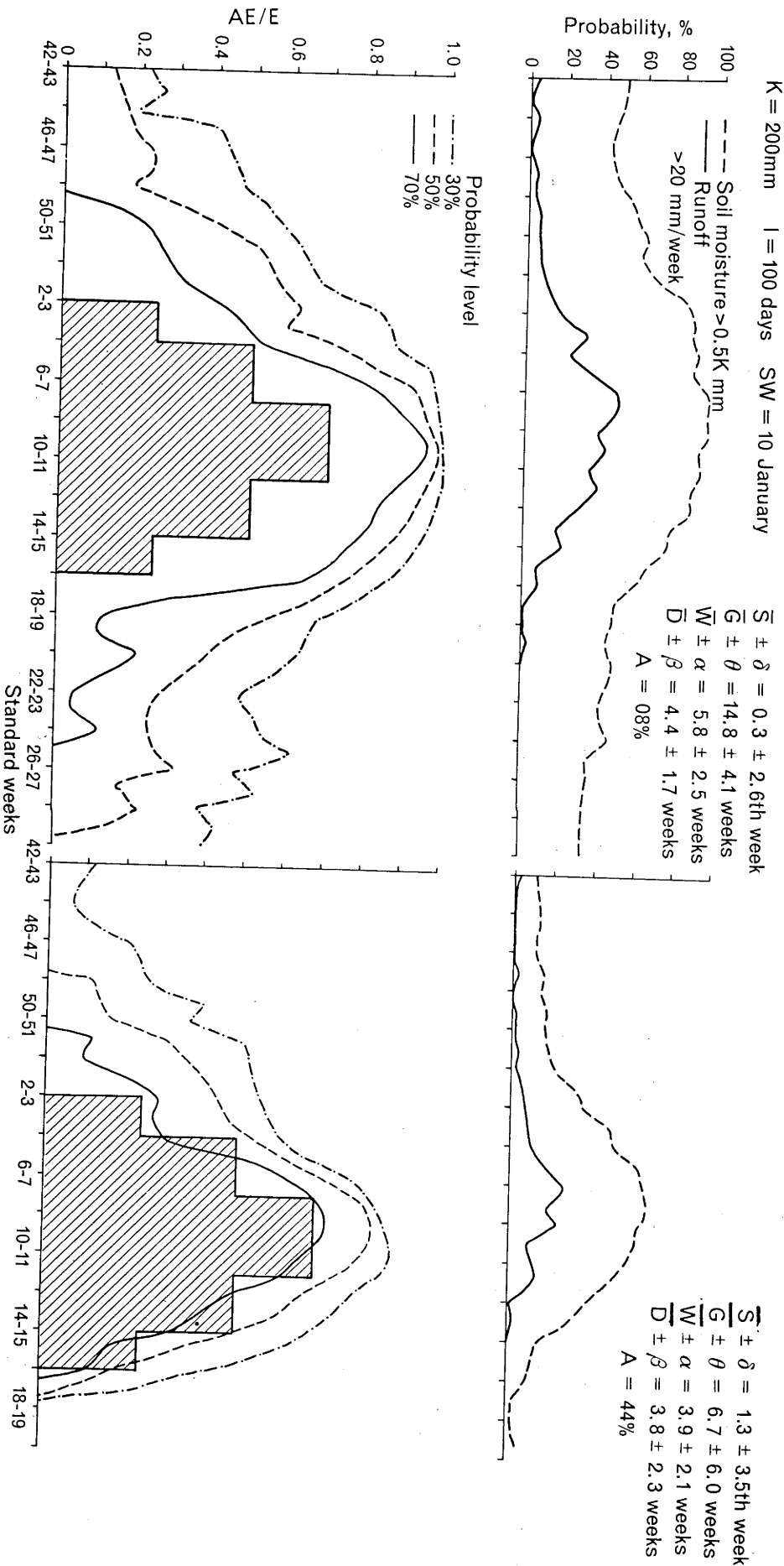


Figure 7-16 : Soil water balance simulation results for Atherton and Mt Surprise under deep black soils ( $K = 200\text{ mm}$ ).

WOODSTOCK (19°36' S, 146°48' E)  
(1234)

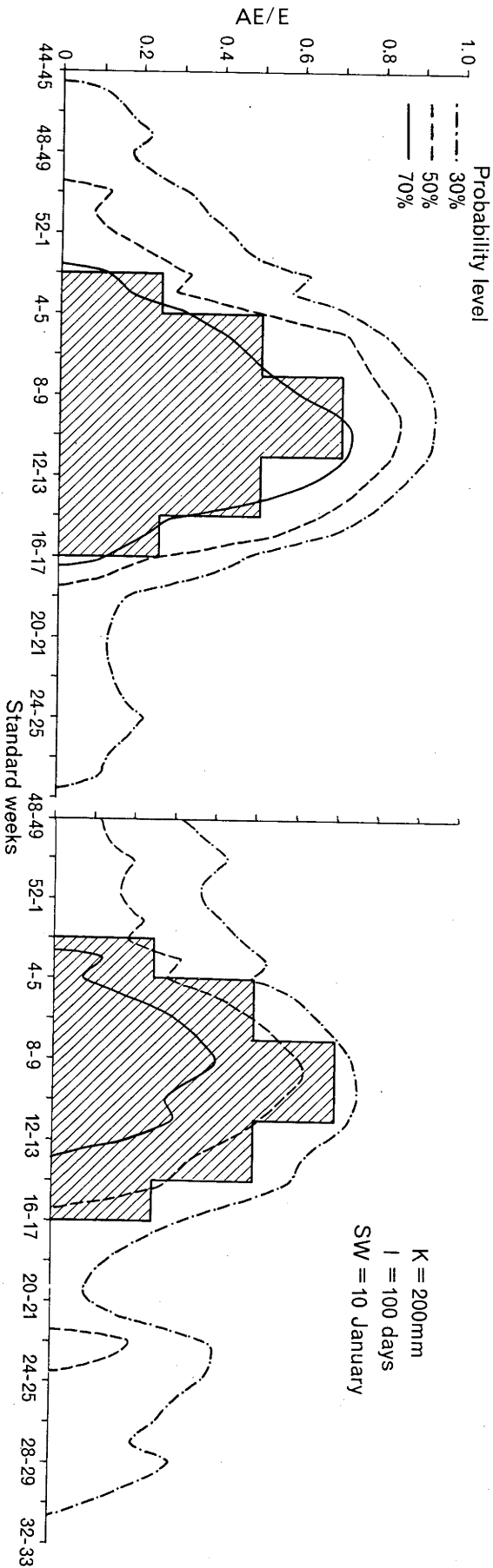
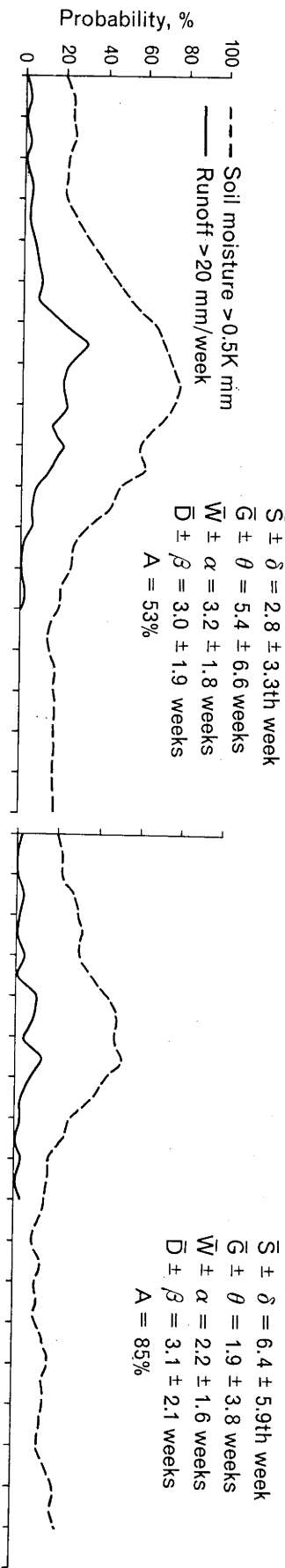
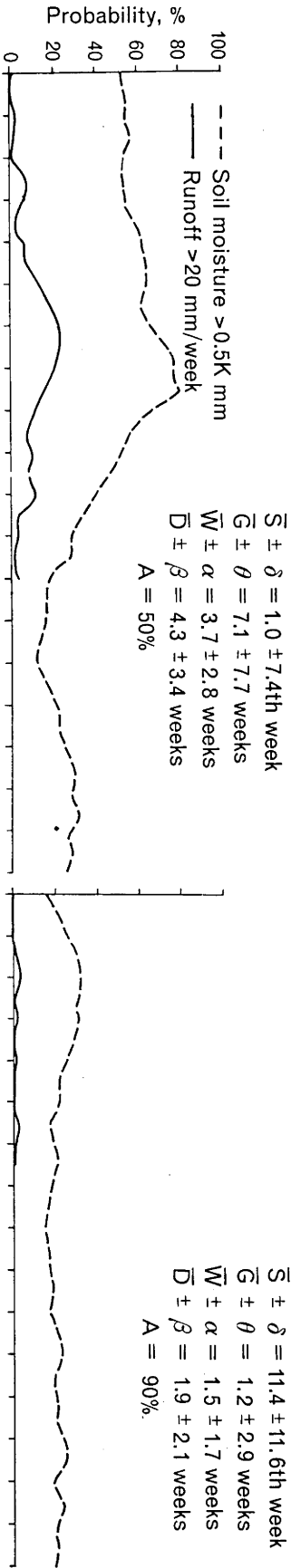


Figure 7-17 : Soil water balance simulation results for Woodstock and Clermont under deep black soils ( $K = 200$  mm).

MARLBOROUGH (22°48' S, 149°54' E)  
(1124)



MITCHELL (26°29' S, 147°58' E)  
(1122)

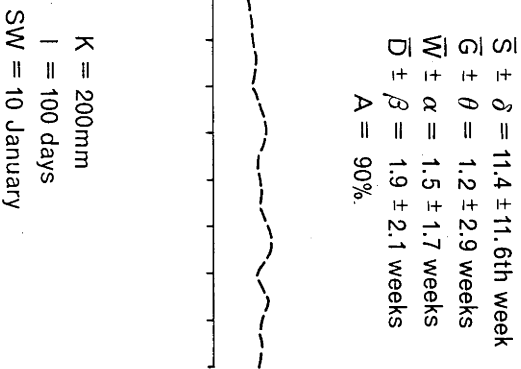


Figure 7-18 : Soil water balance simulation results for Marlborough and Mitchell under deep black soils (K = 200 mm).

rains there is a possibility of adopting a sequential cropping<sup>6</sup> in deep black soils. Also, with sandy soils intercropping could be highly successful. At Mitchell it would always be beneficial to keep the soil fallow during summer and raise a crop in winter, as at Clermont. However, this practice is not good in sandy soils where fodder crops or improved pastures would be more suitable.

In the northern parts the cessation of rains is very sharp. In the SAT this period occurs at the end of April. While in south Queensland it extends to June and July. However, the winter rains alone are not sufficient to raise a second crop but they are highly valuable for a second crop raised on conserved soil moisture. In the southern Queensland area, where summer rains are not significant to raise a crop, land can be kept fallow during summer and a post-rainy season crop could be raised on conserved soil moisture. This practice is not beneficial in sandy soils. Fodder production would be suitable under this situation. With moist periods comparable to the northern parts, intercropping in the south Queensland would be suitable. Where winter rains are substantial these regions are suitable for sequential cropping. In wetter parts of the SAT runoff is considerably higher, and hence runoff recycling is highly beneficial for increasing productivity and for reducing the risk level<sup>7</sup>.

It is also seen from all these diagrams of soil-water balance simulations that when  $W > 4$  weeks the runoff is generally quite high but when dry spells are simultaneously long runoff is considerably low. In the case of sandy soils the appropriate time for sowing is after the mean week of commencement time of sowing rains [S] when the top soil is at field capacity while it is before S if  $\delta$  is small; or after S if  $\delta$  is large in the case of deep soils (vertisols).

---

<sup>6</sup>Smith et al. (1983) state that "Traditionally, dry-land farmers try to grow one crop each year with fallow in the alternate season" (a winter or a summer crop). However, there is an increasing tendency to plant when the soil water store is substantially replenished irrespective of season (Derndt & White, 1976). Waring et al. (1958) found wheat yield was significantly linked with the amount of water held in the soil at sowing. All these observations testify, indirectly, the possibility of occurrence of high risk for dry-land agriculture during the rainy season as observed in the present study. Also, it emphasises that keeping soil fallow is not a good practice always. Therefore, in years of good early rains it is always better to go for sequential cropping in these regions.

<sup>7</sup>Smith et al. (1983) states that "Major areas are irrigated with surface water at Emerald, St. George, Theodore and on the Darling Downs. Large farm dams to store surface runoff for irrigation, are becoming more common."

## 7.5 CLASSIFICATION OF TROPICAL AUSTRALIA

In classifying India, Senegal and Upper Volta into agronomically relevant homogeneous zones the primary criterion was the mean duration of the available effective rainy period (G) since this relates to potential cropping patterns. Further sub-division was based on dependability of sowing period as defined by the standard deviation of the commencement time of sowing rains [8]. These sub-divisions were further divided into groups and sub-groups based on C, A, W and D. The present 82 locations are arranged into these zones, sub-zones, groups and sub-groups and are presented in Table 7-4. The spatial distribution of the sub-divisions are depicted in Fig. 7-19. In all there are 25 sub-groups in the SAT of Australia.

Because of the special characteristic behaviour of northern Australian climate, where the wet spells are longer than dry spells (except for the sub-tropics of southern inland Queensland), the moisture regime is wetter over northern Australia compared to India and west Africa. Therefore, under comparable available effective rainy periods, drought resistant crop varieties can be grown in the Australian situation as compared with India. For example, under similar available effective rainy periods and dependability levels, regions which are suitable for pearl millet in India are suitable for sorghum in Australia. In tropical Australia the most appropriate crops are sorghum, groundnut, cotton, pigeonpea, finger millet, maize and paddy-rice for kharif, and chickpea, safflower, wheat (where temperatures are suitable) for rabi, or any other species proved to be successful over tropical Australia.

In this analysis, stations in the arid and sub-humid zones are also used to obtain an indication of the relative situation at the lower and upper boundaries of the SAT, respectively.

### 7.5.1 Arid zone

Nine arid locations are arranged into four sub-<sup>zones</sup>~~groups~~ according to their level of dependability. The mean available effective rainy period is less than 2 weeks and the c.v. is more than 200%. Probable crop failure years exceed 89%. These characteristics demonstrate their non-suitability for dry-land agriculture whereas they are more suitable for fodder production. The soil water balance simulation results at Derby (30 in 0521)<sup>8</sup> under deep black soils suggests that a single crop could be

<sup>8</sup>30 refer to location no. in Appendix D[D] and 0521 refer to group number in Table 7-4.

Table 7-4 : Agroclimatic classification results (Tropical Australia).

Class <sup>a</sup>	R <sup>b</sup>	Agroclimatic attributes <sup>c</sup>							Location No. (see Appendix-D(D))	
		S	G	C	W	q	D	A		
<b>Arid zone:</b>										
0111	L	6.0	0.0	-	0.0	0.0	0.0	0.0	89	2, 42
	H	6.3	1.0	290	2.3	1.2	2.6	1.8	96	
0221	-	4.4	0.4	350	1.0	0.8	1.3	1.1	95	70
0321	L	2.2	0.2	233	0.3	0.4	0.0	0.0	93	8, 22, 76
	H	2.7	1.2	333	1.8	1.4	1.9	1.6	100	
0521	L	0.5	0.2	230	1.0	1.0	0.5	0.5	94	12, 30, 59
	H	1.5	0.8	550	1.5	1.5	1.5	2.1	100	
<b>Semi-arid zone:</b>										
1122	L	11.6	1.2	197	1.5	1.7	1.9	2.1	81	27, 56
	H	12.5	2.9	233	1.9	2.5	2.0	3.2	90	
1124	L	7.4	6.1	95	2.5	2.2	3.4	3.0	50	36, 51
	H	8.2	7.1	108	3.7	2.3	4.3	3.4	50	
1221	L	3.3	1.4	183	1.9	1.6	2.0	2.1	77	7, 13, 21, 54, 69
	H	5.9	2.2	235	2.4	2.1	3.9	3.0	85	
1222	L	3.1	3.0	157	2.4	2.3	2.4	1.9	74	18, 60
	H	3.1	3.3	157	2.8	2.4	3.0	2.5	77	
1223	L	3.4	3.5	137	3.1	1.5	3.0	2.1	68	24, 53, 71
	H	4.5	4.0	157	3.7	2.7	4.4	2.9	71	
1234	L	3.2	4.5	109	2.6	1.8	2.3	1.6	47	6, 9, 17, 26, 35, 63, 81
	H	4.2	6.8	122	3.7	3.0	3.9	3.2	59	
1235	L	3.4	6.7	87	3.9	2.1	3.8	2.3	36	11, 61
	H	3.5	7.2	90	4.3	2.4	4.1	2.4	44	
1311	L	2.5	1.4	194	1.3	1.5	1.1	1.2	81	14, 49
	H	2.6	1.8	200	2.2	1.8	1.6	1.7	100	
1312	-	2.5	2.5	168	2.8	1.6	2.0	1.8	79	3
1321	L	2.0	3.3	133	2.5	1.1	2.1	1.5	63	20, 31, 67, 78
	H	3.0	4.1	145	3.3	2.2	3.2	1.7	69	
1322	L	2.4	3.6	114	2.6	1.5	2.4	1.7	61	10, 44, 52
	H	3.0	4.3	122	2.9	2.2	2.6	2.0	66	
1333	L	2.1	5.0	100	2.8	1.3	2.5	1.8	55	40, 41, 58
	H	3.0	5.3	124	3.2	2.6	3.4	2.8	59	
1334	L	2.3	5.3	77	2.3	1.9	1.9	1.4	44	64, 80, 82
	H	3.0	6.3	95	3.6	2.8	3.1	2.3	60	
1521	-	1.5	0.8	303	0.7	1.1	1.0	1.7	94	37
1522	-	1.3	2.1	181	2.6	1.3	1.3	1.3	85	16
1523	-	1.2	2.8	138	2.2	1.6	1.5	1.0	68	38
2233	L	3.5	9.3	54	4.1	2.2	3.0	2.3	70	34, 45, 75
	H	4.1	11.8	67	5.3	3.9	4.2	2.5	31	
2313	L	2.3	8.1	67	3.4	1.9	3.2	1.6	31	19, 72, 74
	H	2.9	8.2	72	4.3	2.7	3.3	1.9	38	
2322	L	2.2	9.3	52	3.4	1.3	2.5	1.5	22	32, 47, 77
	H	2.5	10.0	54	4.6	2.2	3.0	2.1	24	
2333	L	2.2	10.4	48	3.8	1.6	3.0	1.8	15	39, 46, 66
	H	2.8	11.6	52	5.3	2.4	4.3	2.1	20	
2341	-	3.0	12.9	36	5.6	2.4	4.3	1.8	09	55
2413	-	1.8	5.1	60	3.8	0.2	2.5	1.7	28	33
3231	-	3.5	14.7	42	5.7	2.9	4.3	2.4	05	65
3232	L	3.2	16.2	30	6.5	2.4	5.0	1.8	00	62, 68
	H	3.2	16.3	33	6.8	3.1	5.7	2.5	00	
3312	L	2.5	13.4	28	5.2	2.1	3.7	1.5	00	4, 23, 48, 57
	H	2.8	16.1	35	6.4	2.7	4.4	2.1	06	
<b>Sub-humid zone:</b>										
6211	L	3.2	16.4	36	4.3	3.2	5.3	2.3	00	25, 43
	H	4.4	18.0	50	7.5	3.3	6.2	2.2	00	
6231	-	3.3	21.7	32	7.7	4.0	6.7	2.6	00	15
6311	-	2.9	17.4	25	8.2	3.0	4.6	1.5	00	5
6321	L	2.1	18.1	14	7.5	1.9	4.6	1.5	00	1, 28, 29
	H	2.4	19.0	20	8.5	2.5	5.5	1.7	00	
6322	-	2.4	19.6	15	10.2	2.0	4.3	1.4	00	79
6411	L	1.8	17.5	14	8.2	2.0	4.1	1.3	00	50, 73
	H	1.9	18.0	22	9.3	2.2	4.4	1.6	00	

<sup>a</sup>The four numbers of a class from left to right respectively represent zone, sub-zone, group and sub-group numbers.

<sup>b</sup>L and H respectively represent the lowest and the highest value of an attribute in that class.

<sup>c</sup>S, G, W, q, D, A are in weeks and C and A are in %.

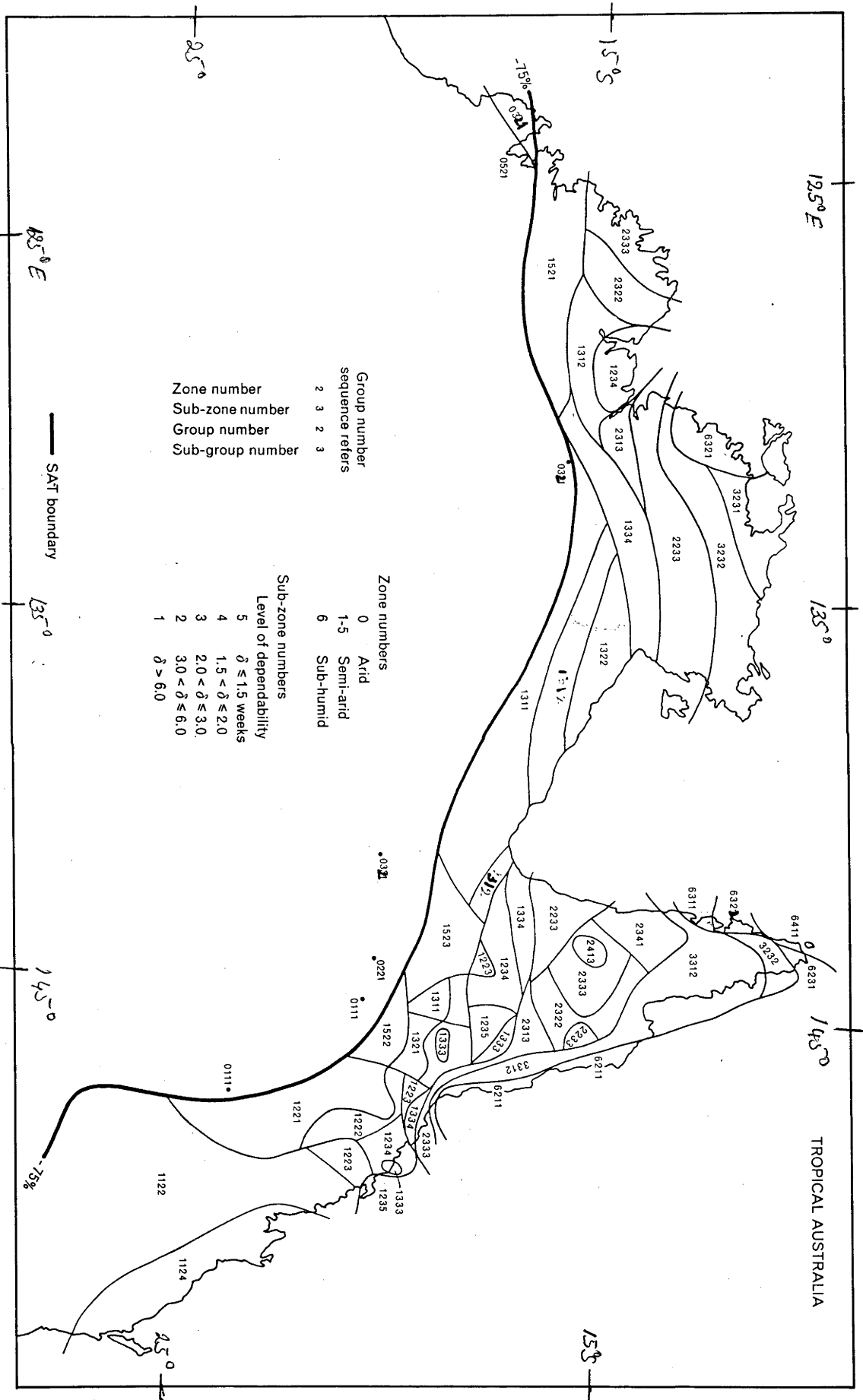


Figure 7-19 : Agroclimatic classification of semi-arid tropical Australia.



successful only one in three years. However, the soil moisture regime presented by AE/E pattern does not represent a continuous period for the same year. There is a possibility of getting a dry period within the available effective rainy period which will adversely affect the food crop production (which needs a continuous good moisture status).

#### 7.5.2 Semi-arid zone

The 63 semi-arid locations are arranged into 25 sub-groups. In the SAT the aridity index (A) goes as high as 100%. The effective rainy period also shows very low values (1.2 weeks) along with c.v. as high as 235%. Two sub-groups (1122, 1124), display very high undependability, eight sub-groups are undependable (1221, 1222, 1223, 1234, 1235, 2333, 3231, 3232), one is moderately dependable (2413), three are highly dependable (1521, 1522, 1523) and the rest are dependable zone (1311, 1312, 1321, 1322, 1333, 1334, 2313, 2322, 2333, 2341, 3312). Dry-seeding is risky in the former two <sup>sub-zones</sup> groupings while in the latter it is feasible.

In sub-groups 1122, 1221, 1311 & 1522 dry-land agriculture is highly risky as there is a possibility of crop failure in more than 75% of the years. They are, however, highly suitable for fodder production. The soil water balance simulation results at Clermont (21 in 1221) and Mitchell (56 in 1221) also support this conclusion. On soils with high water holding capacity there is a possibility of raising a food crop by fallowing during summer and planting in late summer, autumn or early winter, on conserved soil moisture. As mentioned in earlier pages, this technique is, in fact, being practiced by farmers on soils with high water holding capacity such as vertisols and deep and highly fertile alluvial soils with average wheat yields ranging from 1034 kg/ha at Clermont to 1385 kg/ha at Dalby and yields varying as high as 23% (Nix & Fitzpatrick, 1969). Fallowing to conserved soil moisture is not feasible with sandy soils as they have low water storage capacity. Sub-group 1521 is similar to 0521.

In Sub-groups, 1123, 1222, 1223, 1321, 1312, 1322 & 1523 the average available effective rainy period varies between 2 to 5 weeks with a c.v. of 110%–180% and aridity index of 60%–75%. In these regions food crop production could be successful once in three years. This also evident from the Argyle Downs (3 in 1312) simulation results. On deep black soils, keeping the soil fallow during summer and raising a crop in early winter could improve the situation. The Bellary region in India has a

comparable agroclimate where this practice results in higher productivity. This practice may be quite appropriate for regions with large  $\delta$  but for the regions with small  $\delta$  crop mixtures of different maturity dates (like pearl millet of 75 days and sorghum of >90 days) are preferable.

Sub-group 1124 is characterized by high variability in the initial rains and the probability of crop failure is more than 50%. The average available average effective rainy period varies between 6.1 and 7.1 weeks with a c.v. of 95%–100%. Comparison with analogues in India suggest that, with early rains this zone could support sequential cropping on soils with high water holding capacity and intercropping on soils with low water holding capacity. With very late rains intercropping is indicated on soils with high water holding capacity and a short duration single cropping on soils with low water holding capacity<sup>9</sup>. Runoff recycling could be beneficial but runoff is not high in this sub-group and wet spells are of shorter duration than dry spells. Sub-group 1124 is nearly similar to Amritsar and Sikar in India. However, the risk is low for the sites in India while it is high in association with high C in the Australian sites. In India the recommended practice is for a single crop of pearl millet with late rains and sorghum, groundnut or castor with very early rains.

The sub-~~zone~~<sup>group</sup>s 1333 & 1334 with an average available effective rainy period of 5.0–6.3 weeks and c.v. of 77%–124% and aridity index of 40%–60% are suitable for a single crop. The sub-groups 1234 & 1235 are similar to the above two sub-groups except in terms of dependability of initial rains. Because of this, in years of good early rains, intercropping is also possible in deep black soils. This is also evident from the soil water balance simulation results for Woodstock (81 in 1234) and Mt Surprise (61 in 1235). Runoff as such is not high in the deep black soils, but may be considerable in sandy soils. Therefore, runoff recycling may be beneficial in these sub-groups. Sub-group 1234 is similar to Anantapur & Bijapur in India. The recommended practice at Anantapur in sandy soils, with very early rains, is to plant castor and with very late

---

<sup>9</sup>Traditionally the farmers grow wheat on conserved soil moisture on cracking clay soils (vertisols) and fine-textured alluvium with high water holding capacity. The yields are slightly better than at Clermont (1367 kg/ha with a c.v. of 17% at Diloela). However, the experimental station results at Diloela suggest that rainy season single crop sorghum yields are 2251 kg/ha with a c.v. of 52% while post-rainy season single crop wheat yields are 2051 kg/ha with a c.v. of 25% (Nix & Fitzpatrick, 1969). These results clearly demonstrate that with early good rains double and with late rains intercropping on soils with high water holding capacity is more appropriate cropping pattern to increase the productivity.

rains pearl millet or horsegram. At Bijapur in deep black soils with very early good rains the recommended practice is for groundnut/pigeonpea intercropping while with late rains a single sorghum is preferable. The sub-zones 1234 & 1235 are nearly similar to Coimbatore and Kolar in India.

In sub-group 2233 the dependability of initial rains is very low. The average available effective rainy period varies between 9.3 to 11.8 weeks with a c.v. of 54%-67% and an aridity index of 20%-31%. Wet spells are longer than dry spells and wet spells themselves are longer than 4 weeks. Because of these characteristics water-logging is a problem and dry-seeding is risky. Runoff recycling is possible. With good early rains intercropping, and with late rains, single cropping could be successful in both deep black and sandy soils while shallow soils are suitable for single cropping. Some of these observations are also seen from the soil-water balance simulation results at Katherine (45 in 2233). The situation is similar with sub-groups 2313, 2322, 2333 & 2341 except that the dependability is slightly better. These features are also seen from the soil-water balance simulation results at Townsville (74 in 2313). In these sub-groups double cropping is also possible in some years (in years when the early rains are good) in deep black soils. However, because of high c.v. there is a strong possibility of early cessation of rains in many years. To overcome this problem it is always better to grow an intercrop so that even if the rains recede very early, the short duration companion intercrop gives some yield. Sub-group 2233 is nearly similar to Sholapur except that the wet spells are more than the dry spells. The recommended practice at Sholapur in India is for double cropping with very early rains (the first crop being of 60-75 days duration) followed by intercropping of pearl millet/pigeonpea. With very late rains in deep black soils a single sorghum crop is recommended. Sub-group 2313 is nearly similar to Dakar in Senegal; 2322 is nearly similar to Bani in Upper Volta; 2333 is nearly similar to Hyderabad in India and 2341 is nearly similar to Jalgaon in India. However, in all of these sub-groups the dry spells are longer than wet spells in India & west Africa. The recommended practice at Hyderabad in India under deep sandy soils is intercropping of pearl millet/pigeonpea; in deep black soils, with early rains, double cropping of sorghum+chickpea; and with late rains, intercropping of sorghum/pigeonpea. In deep black soils water-logging is a problem.

In sub-group 2413 single cropping could be successful. In sub-groups 3231, 3232 & 3312 with very early rains double cropping and with late rains, intercropping could be successful. This is also evident from the soil-water balance simulation results from Pine Creek (68 in 3232). In this sub-group wet spells are longer than 5 weeks and dry spells are fewer than wet spells. Water-logging is, therefore, a major problem in deep black soils. Dry-seeding is risky. The soil-water balance results at Atherton (4 in 3312) also support this conclusion. Runoff is considerable. The sub-group 2413 is similar to Matam in Upper Volta and 3231 & 3232 are nearly similar to Ramanathapuram in India and 3312 is nearly similar to Osmanbad & Aurangabad in India.

### 7.5.3 Sub-humid zone

The ten locations in the sub-humid zone are arranged into six <sup>sub-zones/groups/</sup>sub-groups based on dependability and the duration of the available effective rainy period. In this zone the average available effective rainy period is more than 16 weeks with c.v. less than 40%. The wet spells are more than 7 weeks with wet spells being more than dry spells. Most of these <sup>sub-zones/groups/</sup>sub-groups are suitable for double cropping. These <sup>sub-zones/groups/</sup>groups are similar to northeast Indian sub-humid locations. In the case of India the recommended practice in these sub-zones <sup>sub-zones/groups/</sup>is paddy-rice-based double cropping for deep black soils and finger millet-based double cropping for deep sandy soils.

Niger locations in west Africa seems to follow the north Australian situation, even with respect to wet and dry spells but not in terms of their relative magnitude. Figure 7-20 presents the soil-water balance simulation results for two Niger locations. The same diagram also presents the agroclimatic attributes. The Niger locations differ from northern Australia in terms of dependability, where the commencement time of sowing rains are less variable but cessation time of rains do show wide variation. Because of this the recommended practice at Niamey Ville and Maradi in Niger is a mixture of sorghum (late maturing companion crop) and pearl millet (early maturing companion crop). The success of these crops is very high (Fig. 7-20) in west Africa.

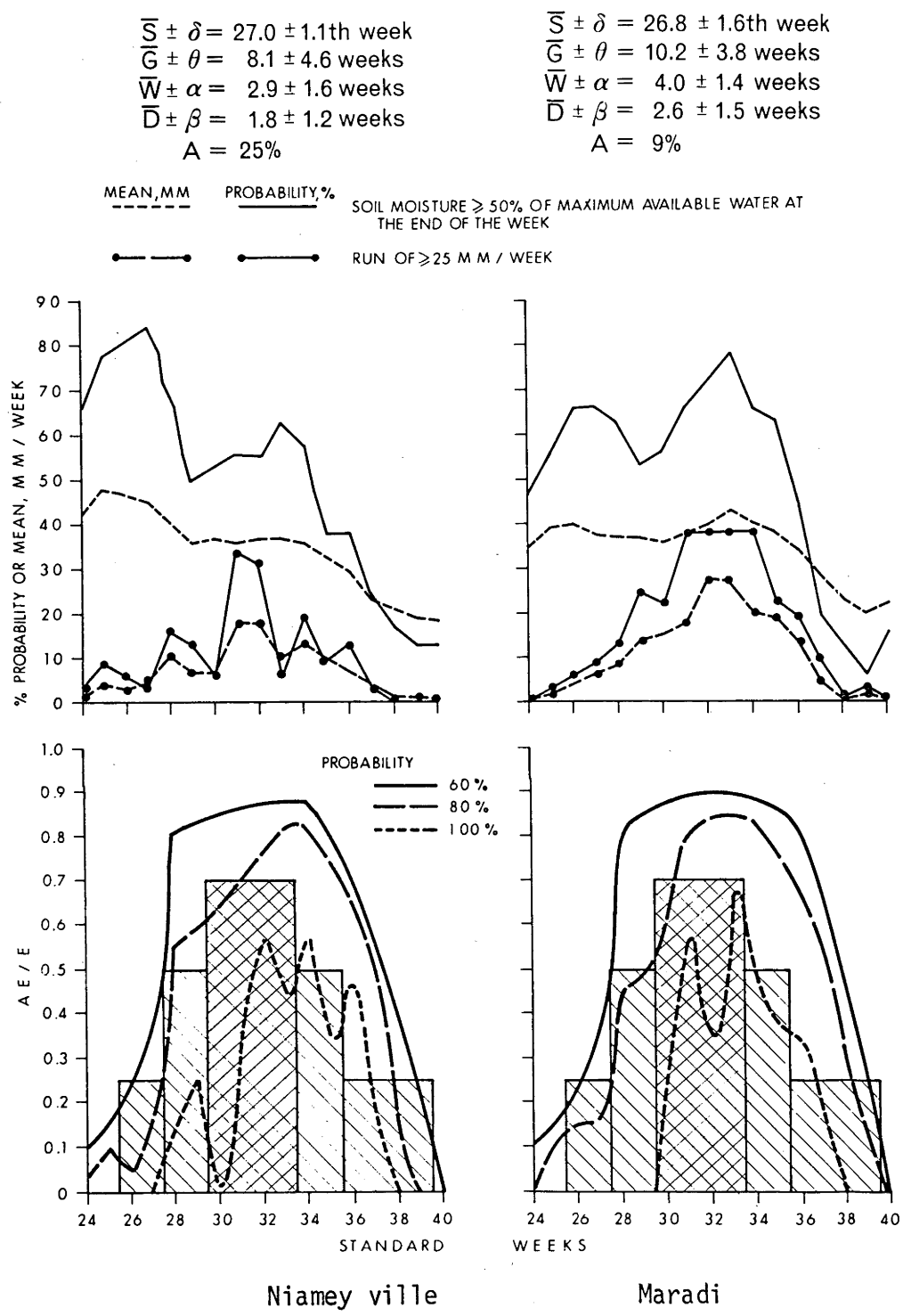


Figure 7-20 : Soil water balance simulation results for two Niger locations (Niamey Ville and Maradi) in west Africa.

## 7.6 SUMMARY

This part of the study presents an agroclimatic classification and the potential for agricultural productivity in tropical Australia. Agroclimatic attributes are computed for 82 locations using the methodology suggested in Chapter 3. The spatial distribution of the attributes suggest that:

- The onset and cessation times of rains are highly variable, particularly in southern Queensland. This affects the stability of crop production substantially. Hence careful planning is required in terms of time of sowing as well as in the identification of suitable cropping patterns accordingly. Dry-seeding is generally risky in tropical Australia.
- Wet spells, within the available effective rainy period, are longer than dry spells in the northern parts while they are fewer than dry spells over south Queensland. Regions in the northern part having periods of more than 3 wet weeks appear to face water-logging problems during crop growing season.
- Under the same mean annual rainfall the available effective rainy period is considerably lower than in India and west Africa. Under the same average available effective rainy periods the wet spells are nearly the same as those in India but the dry spells are fewer. (Because of this there is a strong possibility of good runoff which could be utilized by collection and recycling). However, this situation may pose problems for various cultural operations such as harvesting of a rainy season crop. Under comparable wet spells water-logging is more severe in Australia than in India.

The correlation study between different agroclimatic variables suggests that:

Curvilinear relationships are observed for:

1. the c.v. of the available effective rainy period versus the average available effective rainy period;
2. wet spells versus the average available effective rainy period;
3. wet spells versus dry spells.

Linear relationships are observed for:

1. the standard deviation of the commencement time of sowing rains versus the c.v. of available effective rainy period;
2. the average available effective rainy period versus dry spells.

Except for the last, all other patterns are similar to India and west Africa.

The 82 locations are arranged according to arid, semi-arid and sub-humid zones. In the arid zone there are four sub-groups, in the sub-humid six sub-groups and 25 sub-groups in the semi-arid zone. Some of the characteristics and their agronomic relevance are summarised below:

- Arid locations with an average available effective rainy period of less than 2 weeks, a high c.v. (more than 200%) and high risk (more than 80%) are more suitable for fodder production rather than food crop production.
- Sub-humid locations appear to be similar to the northeast Indian sub-humid zone around Ranchi. These regions are highly suitable for paddy rice- or finger millet-based double cropping respectively in the vertisols and alfisols. Water-logging is severe. Dry-seeding is risky and there is a high possibility of rains occurring at harvest time as well as less field work days available for cultural operations. Hence, these regions are unsuitable for dry-land crops during the rainy season.
- The majority of wetter semi-arid locations appear to be similar to central India except that in India dry spells are longer than wet spells. Because of this, under comparable available effective rainy periods, crop varieties having less drought tolerance can be grown in the Australian situation compared with India. Katherine is similar to Sholapur, while Giru near Townsville is similar to Hyderabad in India. In deep black soils intercropping (100/180 days) is successful with occasional double cropping (100+100 days) at Hyderabad and in sandy soils single crop of 100 days is successful with occasional intercropping.
- The regions under the SAT with more than 13 weeks of average available effective rainy period are suitable for double cropping while regions with 8-13 weeks of average available effective rainy period are more suitable for intercropping. Locations with 4-8 weeks of average available effective rainy period are more suitable for single cropping if the initial rains are dependable (sub-zones 3 to 5 in zone 1). With high undependability of initial rains (sub-zones 1 & 2 in zone 1), such as south Queensland, intercropping would be suitable for very early, good rains, situations while single crop would be better with late rains. Under deep soils with high water holding capacity of sub-zones 1 & 2 in zone 1 are more suitable for summer fallow winter cropping. Regions with less than 4 weeks of average

available effective rainy period are more suitable for fodder production rather than food crop production. [However, in some years it is possible to raise a dry-land crop on soils with high water holding capacity with conserved soil moisture in winter.] Therefore, in tropical Australia, the regions with more than 4 weeks of the average available effective rainy period like in India are useful for dry-land agriculture.

The spatial distributions presented in this chapter are based on locations sparsely and non-uniformly distributed over tropical Australia. Therefore, for a more comprehensive and detailed demarcation of the boundaries for individual parameters, as well as for agroclimatic classification, a closer network of stations is essential to monitor changes in climatic parameters at the local or micro-scale level. This is also true in the case of India.

In general agroclimatic attributes over northern Australia present a similar pattern to India and west Africa, but they differ in dry and wet spells. At almost all locations wet spells are longer than dry spells in the case of northern Australia. Because of this many of the locations in the drier parts of SAT and arid zone follow the Indian and west African situation up to zone, sub-zone and group level but they differ at sub-group level. However, on wetter side of the SAT and sub-humid zone it appears that they are similar, even at sub-group level, to some of the north Indian locations. Sorghum-, groundnut-, finger millet-, maize- and paddy-rice-based cropping patterns are more successful from drier zones to wetter zones. In the case of north Australia it is always preferable to grow crops as mixtures with different maturity groups (i) to avoid the risk due to early cessation of rains, and (ii) to better utilize the rains during late cessation of rains as the cessation of rains show high variation similar to onset of rains. Water-logging is a problem at many of the zones of SAT Australia and dry-seeding is generally risky.

Some of the cropping patterns suggested based on Indian and west African examples appear to be valid when verified with crop data of a few locations. The Niger locations in west Africa appear to be similar to northern Australia even with wet and dry spells but they differ in terms of dependability of initial rains, where they are low.

From this study it can be inferred that the methodology suggested in the previous chapters could be successfully extended to other SAT regions. The methodology could be extended to arid and sub-humid regions in the tropics and extra-tropical regions with suitable modifications.



## CHAPTER 8

### CONCLUSIONS AND SUGGESTIONS

#### 8.1 INTRODUCTION

The objective of this study is (i) to define the semi-arid tropics and to identify these regions with reference to selected countries; and (ii) to sub-divide the semi-arid tropics into agronomically-relevant homogeneous zones that facilitate the transfer of well tested, site-specific, dry-land technology by identifying and/or developing suitable procedures.

#### 8.2 DEMARCATION OF THE SEMI-ARID TROPICS (SAT)

In the present study the SAT refer to the dry-land agricultural belt. The major crops of this zone are pearl millet, sorghum, pigeonpea, and groundnut. "Tropics" are defined [following Koppen, 1936] as the regions with mean annual temperature  $\geq 18^{\circ}\text{C}$ . However, there is a great diversity in the usage and practical application of the term "semi-arid". From the literature review it was appeared appropriate to look into the following three methods to consider and compare their suitability for the demarcation of the semi-arid zone. They are:

1. Troll's humid period (Troll, 1965);
2. Hargreaves' dependable moist period (Hargreaves, 1971);
3. Modified Thornthwaite's annual moisture index (Reddy & Reddy, 1973).

The first two approaches use the length of the moist period and the third uses the annual moisture index. For the comparison of these three approaches data from India, Africa, Australia, Brazil and Thailand, were used, representing four continents that have climatic patterns varying from deserts to rain forests.

The modified Thornthwaite's approach best fits existing patterns. The semi-arid tropics (SAT) are thus defined as regions with a mean annual

temperature  $> 18^{\circ}\text{C}$  and the mean annual rainfall meets 25% to 75% of the mean annual potential evapotranspiration. The SAT, according to this procedure, includes major dry-land agricultural zones with mean annual rainfall varying between about 500 and 1250 mm. Major dry-land crops of this zone are pearl millet, sorghum, groundnut, pigeonpea etc.

### 8.3 AGROCLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS [SAT]

The SAT map, as demarcated using the modified Thornthwaite's approach, presents uniformity in terms of dry-land agricultural zones, but on a broad scale there are significant internal variations in terms of their production potential.

Although high temperatures and high radiation encourage rapid growth, crop production is limited by rainfall patterns. In the past few decades methods have been proposed to characterize such parameters. Using these methods, the variables are mostly estimated from average monthly, seasonal and annual rainfall based on long-term weather records, and consequently they have limited practical applicability in agricultural production studies and in the transfer of site-specific technology. However, the basic concepts underlying these methods are very valuable aids for further development in this direction. In dry-farming not only is the available moist period, is important, for proper planning of seeding operations, but also the time of its commencement. The variability of weather from year-to-year on a seasonal basis is essential for identifying crop and cropping patterns, land and water management practices and their associated risk.

#### 8.3.1 Method for the derivation of classificatory variables

To answer some of these questions, based on actual time sequence of weekly rainfall and potential evapotranspiration data over periods of more than 15 years, a simple method is proposed. This method yields the mean week of commencement time of sowing rains (S) and its variability ( $s$ ); the mean available effective rainy period (G) and its variability (C); the mean wet (W) and dry (D) weeks within the available effective rainy period and their variability ( $\alpha$ ,  $\beta$ ); and the percent crop failure years or level of risk associated with dry-land agriculture (A). This procedure is developed with special reference to the SAT. Here, the effective rainy period differs from the growing period, where the latter includes the period

available from the conserved soil moisture after the rains recede, in addition to the available effective rainy period. The period available from conserved moisture varies according to the storage capacity of the soils.

The derivation of principles for the transfer of site specific technology was based on data from 199 locations in India and two west African countries (Senegal and Upper Volta). The data of 82 locations from tropical Australia were subsequently used to test the applicability of the derived model.

### 8.3.2 Dissimilarities in the pattern of agroclimatic variables

Excluding S, the remaining 8 variables [ $\delta$ , G, C, W,  $\alpha$ , D,  $\beta$  and A] define production potential, whereas S is useful for planning cropping strategies. Using the 8 variables in regression analysis, 3 dissimilarity variables [G', W' and D'] have been derived. These three variables relate to dissimilarities at local, regional and continental scale caused by orography, proximity to sea or regional circulation patterns and general circulation patterns, respectively.

The basic dissimilarities observed between India, west Africa and tropical Australia are:

- for a similar mean annual rainfall, the corresponding available effective rainy period is longer in west Africa and shorter in tropical Australia;
- for a similar mean available effective rainy period, the corresponding wet periods are shorter in west Africa and longer in tropical Australia;
- the commencement and cessation times of effective rains show considerable variation in association with local factors in India and tropical Australia; in west Africa, where the local effects are insignificant, considerable variation in cessation time of effective rains, in association with regional factors, is observed.

The first two dissimilarities define continental differences while the third defines those at regional and local scales.

### 8.3.3 Characterization of production parameters

The 8 production parameters are characterized by their relevance to dry-farming practices. A soil-water balance simulation and agronomic data for selected locations in India have been used to assist in this analysis. the following successful cropping systems, on similar soil types with different levels of dependability, are identified.

[1] With high variability in both the commencement and cessation times of effective rains ( $\delta$  and  $C$ ) then:

- if the available effective rainy period is short ( $\leq 8$  weeks) and with early sowing rains, a long duration single crop or intercropping should be adopted, but if these rains are late then a single crop should be grown on alfisols whereas on vertisols a rabi single crop should follow a kharif fallow;
- if the available effective rainy period is moderately long (8–13 weeks), and with early sowing rains, intercropping should be adopted, but if these rains are late a single crop should be grown on alfisols, and on vertisols either double cropping [with early rains] or intercropping [with late rains] should be practiced;
- if the available effective rainy period is long ( $> 13$  weeks), and with early sowing rains, double crops should be grown, but with late rains intercropping should be practiced.

[2] Under more stable commencement and cessation times of effective rains ( $\delta$  and  $C$  small) then:

- with a short available effective rainy period a single crop should be grown;
- with a moderate available effective rainy period, intercropping should be practiced on alfisols and double cropping on vertisols;
- with a long available effective rainy period, double cropping is preferable.

However, the crop varieties that are suitable for these cropping patterns also vary significantly. They are associated more with the soil type, and the wet and dry spells within the available effective rainy period. The following successful crop varieties under different conditions are identified.

- on alfisols, millets should be grown, and on vertisols, sorghum, maize, paddy-rice, etc., are the preferred crops;
- when wet spells are  $> 7$  weeks and the period of dry spells are  $\leq 70\%$  the period of wet spells, then paddy-rice (with early rains) and maize (with late rains) are the preferred crops on vertisols. Under similar rainfall conditions, finger millet is the most suitable crop on alfisols;
- when the wet spells are  $\leq 7$  weeks, but are still more than dry spells, then maize (or occasionally paddy-rice) should be grown on vertisols and finger millet on alfisols;
- when the wet spells are less than dry spells either pearl millet, sorghum, groundnut, castor, pigeonpea, cotton or finger millet are found to be more remunerative.

#### 8.3.4 Agroclimatic classification

In the present study numerical taxonomic procedures have been adopted to sub-divide the SAT into agronomically relevant homogeneous zones. Among the three numerical procedures used in this study, the minimum spanning tree and ordination techniques appear to be more useful for exploratory data analysis. However, ordination can be used to generate new, standardized variables that are fewer in number with less noise, explaining variance in the data set, than the original variables. Under the third numerical taxonomic procedure (clustering) there are several strategies and algorithms existing in the literature. Similar to classification techniques, there are several similarity measures that could be used to integrate the variables. Unfortunately as yet there is no accepted test procedure to identify the most appropriate method for a given set of data. Most of the test procedures that exist in the literature specify the mathematical soundness of the procedure rather than answering the question "with a given set of data which procedure presents the least mis-classifications?"

In the absence of such a test procedure, that which is least biased by mis-classifications was identified through subjective judgement after trying all possible procedures. The dendrogram obtained using the data matrix of 11 variables (8-production parameters and 3-dissimilarity parameters) for 190 locations from India, Senegal and Upper Volta using a standardized Euclidean similarity metric in conjunction with the UPQMA (unweighted pair group methods using arithmetic means) fusion strategy

under a clustering technique was found to produce better classes than the other combinations. However, the UPGMA-Euclidean metric combination using a 7-principal coordinate data matrix has given the most acceptable results. These results are highly valid mathematically if no significance is attached between agronomic practices and certain variables. Hence, some of these classes are not homogeneous in terms of their ability to define the level of dependability, which in turn defines the level of dry-seeding feasibility, and wet spells which define water-logging hazards. Therefore, in order to make these groups more relevant to agronomic planning, and to characterize them in terms of agroclimatic variables, so that new locations can easily be fitted into these classes (which is primarily important for the transfer of site-specific dry-land technology), they were adjusted subjectively by keeping to the objective frame-work obtained through numerical techniques.

Agronomically relevant classes have been achieved as follows: The 190 locations were arranged into arid, semi-arid and sub-humid zones based on a modified Thornthwaite approach. The basic characteristics of these zones in terms of agroclimatic variables are surprisingly different. For example, in the arid zone, the available effective rainy period is  $\leq 5$  weeks with an aridity index  $> 60\%$ . In the sub-humid zone, the wet spells are  $> 7$  weeks with dry spells being  $< 70\%$  of wet spells, within the average available effective rainy period  $> 16$  weeks and with an aridity index  $\leq 5\%$ . Also, wet spells constitute  $\geq 40\%$  of the available effective rainy period and dry spells constitute  $\leq 30\%$  of the available effective rainy period. The results of numerical analysis suggest that, with few exceptions, classes are separated primarily by the mean available effective rainy period with values  $\leq 8$ , 8-13, 13-18, 18-21 and  $> 21$  weeks (similar to those obtained earlier in comparison with cropping patterns). These 5 zones correspond to 5 major cropping patterns, namely: single, single/inter, inter/double, double (with a medium duration, 90-120 days, kharif), and double (with long duration, 120-150 days, kharif). These patterns represent a highly dependable rainfall situation and need to be modified accordingly, with a less dependable rainfall. Therefore, based on the dependability level, expressed as variability in the commencement time of sowing rains, each of the 5 zones were further divided into 5 sub-zones. They are:  $\leq 1.5$ , 1.5-2.0, 2.0-3.0, 3.0-6.0 and  $> 6.0$  weeks. These are the groups defined in terms of dry-seeding feasibility.

The majority of these sub-groups are also revealed in the numerical analysis results, except under lower ranges in a few cases. To account for other variables that relate to risk, water-logging hazard, or areas that need management of soil etc., the sub-zones were further arranged into groups and sub-groups using other agroclimatic variables namely: the percent of crop failure years, the coefficient of variation of available effective rainy period, and wet and dry spells, and their standard deviations, within the available effective rainy period. These represent the classes obtained using the numerical technique after making minor adjustments at sub-zone level. However, the groups and sub-groups were not quantified like zones and sub-zones. To make the groups and sub-groups more systematic, large data sets both of crops and agroclimatic variables are essential, and these are not available to the author. At a future date, when such information is available, such quantification could be attempted.

Some of the inferences made with reference to Senegal and Upper Volta (derived from Indian experience), agree with the experimental findings relating to sowing time and probable cropping patterns.

The derived zones and sub-zones of the SAT are straightforward, easily memorised and make sense agronomically. Given the class structure it is easy to add new locations without further numerical analysis. Such an analysis is attempted with an independent data set for tropical Australia using the data for 82 locations. The inferences made from this analysis agree with experimental findings.

The majority of the material presented in this thesis has been published in international forums, namely:

## Chapter 2

- Reddy, S.J. 1983. Climatic classification: The semi-arid tropics and its environment – a review. *Pesq. Agropec. Bras.*, Brasilia, 18: 823-847.

## Chapter 3

- Reddy, S.J. 1983. Agroclimatic classification of the semi-arid tropics: I. A method for the computation of classificatory variables. *Agric. Meteorol.*, 30: 185-200.

## Chapter 4

- Reddy, S.J. 1983. Agroclimatic classification of the semi-arid

tropics: II. Identification of classificatory variables. Agric. Meteorol., 30:201-219.

## Chapter 5

- Reddy, S.J. 1984. Agroclimatic classification of the semi-arid tropics: III. Characteristics of variables relevant to crop production potential. Agric. Meteorol., 30:269-292.

## Chapter 6

- Reddy, S.J. 1984. Agroclimatic classification of the semi-arid tropics: IV. Classification of India, Senegal and Upper Volta. Agric. Meteorol., 30:293-325.

## Chapter 7

- Part of this chapter only -
- Williams, J., Day, K.J., Isbell, R.F. & Reddy, S.J. 1983. Climate and soil constraint to agricultural development. In "Agroresearch for the semi-arid tropics: Northern Australia". R.C. Muchow (Ed.), University of Queensland Press, Brisbane.

## Appendix F

- Reddy, S.J. 1983. Agroclimatic classification: Numerical taxonomic procedures - a review. Pesq. Agropec. Bras., Brasilia, 18:435-457.

## 8.4 SUGGESTED FUTURE AREAS OF RESEARCH

1. The procedure described in this study could be extended to arid and sub-humid zones by identifying the appropriate limits for pasture and wet-land crop productivity, respectively.
2. The procedure could also be extended to temperate zones, but the concept would need to be tagged to temperature regimes using the degree-day concept or some other suitable procedure.
3. The results of the present study relate to locations under one prominent rainfall season or two separated rainfall seasons. However, in addition to these regimes, there are several patterns. One such pattern is continuous rainfall for two seasons with the main rainy season in summer. Under this



situation some of the crops and/or cropping patterns will differ. This type of environment is more suitable for double cropping with crops less sensitive to rains at physiological maturity stage. So, more details need to be worked out for such situations (even though the majority of the rainfall patterns are of the former types).

4. One of the important meteorological conditions that needs to be introduced at the stage of interpretation of results (with regard to farming systems) is the climatic cycle. This is, particularly, important in the southern hemisphere stations where it is clearly evident.

Some of these aspects (3 & 4) have been attempted using data from Mozambique in southern Africa, but this work is not part of the present study. Some relevant reports are:

- Reddy, S.J. 1984. Agroclimatic resource inventory of Mozambique: IIa. Suggested farming systems and the calculated associated risks for selected locations. Comunicaçao No. 19b, INIA, Dept. Land & Water, Maputo [FAO/MOZ/81/015], 53p.
- Reddy, S.J. 1985. Agroclimatic resource inventory of Mozambique: IIb. Suggested farming systems and the calculated associated risks for southern Mozambique. Comunicaçao No. 24, INIA, Dept. Land & Water, Maputo [FAO/MOZ/81/015], 160p.

One final important factor which needs to be assessed is crop productivity. Such a study would help long term planning of food exports or imports. Therefore, for the identified farming systems, using regional crop-weather-soil models, the expected trend in the yields could be worked out, where such models are available.

## BIBLIOGRAPHY

- Anderson, A.J.B. 1966. **A review of some recent developments in numerical Taxonomy.** M.Sc. Thesis. University of Aberdeen, Scotland.
- Anderson, A.J.B. 1971. **Numerical Examination of multivariate soil samples.** J. Int. Assoc. Math. Geol., 3:1-15.
- Angstrom, A. 1924. **Solar and terrestrial radiation.** Quart. J. Roy. Met. Soc., 50:121-126.
- Arkin, G.F., Vanderlip, R.L. & Ritchie, J.T. 1976. **A dynamic grain sorghum growth model.** Trans. ASAE, 19:622-630.
- Arkely, R.J. 1976. **Statistical methods in soil classification research.** Adv. Agron., 28:36-70.
- Aubert, G. & Tavernier, R. 1972. **Soil Survey.** In Soils of the humid tropics. Natl. Acad. Sci., Washington, USA. pp.17-44.
- Austin, M.P. & Nix, H.A. 1978. **Regional classification of climate and its relation to Australian rangeland.** In Studies of the Australian Arid Zone. III. Water in rangelands. CSIRO, Melbourne, pp.9-17.
- Austin, M.P. & Yapp, G.A. 1978. **Definition of rainfall regions of South-Eastern Australia by numerical classification methods.** Arch. Met. Geoph. Biokl. Ser. B, 26:121-142.
- Barnet, T.P. 1977. **The principal time and space scales of the pacific trade wind fields.** J. Atmos. Sci., 34:221-236.
- Belbin, L. 1982. **Fuse: A fortran-4 program for cluster analysis fusion of mini-computers.** CSIRO, Canberra.
- Berndt, R.D. & White, B.J. 1976. **A simulation-based evaluation of three cropping systems on cracking clay soils in a summer rainfall environment.** Agric. meteorol., 16:211-229.
- Berry, F.A., Bollay, E. & Beers, N.R. 1973. **Handbook of Meteorology.** McGraw-Hill Book Co., New York.
- Binswanger, H.P., Virmani, S.M. & Kampen, J. 1980. **Farming systems components for selected areas in India: Evidence from ICRISAT.** Res. Bull. No. 7, ICRISAT Patancheru P.O., A.P., India. 40p.

- Black, T.N., Bouyhton, C.W. & Prescott, J.A. 1954. **Solar radiation and the duration of sunshine.** Quart. J. Roy. Met. Soc., 80: 231-235.
- Boyce, A.J. 1969. Mapping diversity: a comparative study of some numerical methods. In Proc. Numerical Taxonomy, A.J. Cole [Ed.], Academic Press, London, pp.1-30.
- Boyko, H. 1962. Old and new principles of phytobiological climatic classification. In Proc. Second Intern. Bioclimatological congress, The Roy. Soc. Med., London, Pergoman Press, Oxford, pp.113-127.
- Bray, J.R. & Curtis, J.T. 1957. An ordination of the upland forest communities of south Wisconsin. Ecol. Monogr., 27: 325-349.
- Brown, L.H. & Cocheme, J. 1968. A study of the agroclimatology of the highlands of eastern Africa. FAO/UNESCO/WMO Inter-agency Project, Tech. Rept., Rome, 330p.
- Budyako, M.K. 1956. Heat balance of the earth's surface. Translated by N. Stepanova, U.S.W.B., Washington D.C. [1958].
- Burgos, J.J. 1958. Agroclimatic classification and representations. Rept. on The application, value of climatic and agroclimatic classifications for agricultural purposes, WMO Comm. for Agric. Meteorol., Second Session, Warlow, 41p.
- Burgos, J.J. 1968. World trends in agroclimatic surveys. In Proc. Reading Symp. on Agroclimatological methods, Natural Resources Res., No.7, UNESCO, pp.211-224.
- Burr, E.J. 1968. Cluster sorting with mixed character types: I. Standardization of character values. Aust. Comput. J., 1: 97-99.
- Burr, E.J. 1970. Cluster sorting with mixed character types. II. Fusion strategies. Aust. Comput. J., 2: 98-103.
- Cain, A.J. & Harrison, G.A. 1958. An analysis of the taxonomists judgement of affinity. Proc. Zool. Soc., London, 131: 85-98.
- Catell, B. 1952. Factor analysis. Harper, New York.
- Chang, Jen-Hu. 1981. A climatological consideration of the transfer of agricultural technology. Agric. Meteorol., 25: 1-13.

- Charreau, C. 1974. **Systems of cropping in the dry tropical zone of west Africa - with special reference to Senegal.** In Proc. Intern. Workshop on Farming Systems. ICRISAT, Hyderabad, India. pp.443-468.
- Clifford, H.T. & Stephenson, W. 1975. **An introduction to numerical classification.** Academic press, London.
- Cocheme, J. & Franquin, P. 1967. **A study of the agroclimatology of the semi-arid areas south of the Sahara in west Africa.** FAO/UNESCO/WMO Inter-agency Project Tech. Rept., UNESCO. pp.117-129.
- Cormac, R.M. 1971. **A review of classification.** Roy. Stat. Soc. A. 134:321-367.
- Craddock, J.M. 1973. Problems and prospects for eigenvector analysis in meteorology. *The Statistician*, 22: 133-145.
- Craddock, J.M. & Flood, C.R. 1969. Eigenvectors for representing the 500 mb geopotential surface over the northern hemisphere. *Quart. J. Roy. Met. Soc.*, 95:576-593.
- Dancette, C. 1978. **Water requirements and adaptation to the rainy season of millet in Senegal.** In Proc. Agroclimatological needs of the semi-arid tropics, ICRISAT, Patancheru, P.O., A.P., India. pp.106-120.
- DSBM 1975. **Rainfall statistics: Australia [metric edition].** Dept. of Sci. Bureau of Meteorol., A.G.P.S., Canberra.
- Dyer, T.G.J. 1975. The assignment of rainfall stations into homogeneous groups: an application of principal components analysis. *Quart. J. Roy. Met. Soc.*, 101:1005-1013.
- Eagleman, J.R. 1976. **The visualization of climate.** Lexington Books, D.C. Heath & Co., Toronto.
- Easter, K.W. & Abel, M.E. 1973. **cropping regions in India.** Economic Development Centre, Bull. No. 1, Univ. Minnesota.
- Fager, E.W. & McGowan, J.A. 1963. **Zooplankton Species groups in northern pacific.** *Science*, 140:453-460.
- Fitz, S. 1949. **Solar radiation during cloudless days.** Heating and Ventilating.

- Fitzpatrick, E.A. & Nix, H.A. 1970. **The climatic factor in Australian grassland ecology.** In Australian grasslands. T.M. Moore (Ed.), Aust. Nat. Univ. Press. Canberra. pp.1-26.
- Fitzpatrick, E.A. & Stern, W.R. 1965. **Components of the radiation balance of irrigated plots in a dry monsoonal environment.** J. Appl. Meteorol., 4:649-660.
- Florek, K. et al. 1951. **Taksonomia Wacławska.** Przegl. Antropol., XVII:193-207. Poznań.
- Frere, M. 1978. **A method for the practical application of the Peman formula for the estimation of potential evapotranspiration and evaporation from a free water surface.** FAO. AGP:Ecol. 1.
- Gadgil, S. & Joshi, N.V. 1981. Use of principal component analysis in rational classification of climates. In Proc. on Climatic classification: a consultant meeting, ICRISAT Patancheru P.O., A.P., India. pp.17-26.
- Gausson, H. 1954. **Theorie et classification des climats et des microclimats.** 8 Congr. Internat. Bot., Paris. Sec. 7.
- Glover, J. & McCulloch, J.S.G.I. 1958. The empirical relation between solar radiation and hours of sunshine. Quart. J. Roy. Met. Soc., 84:172-195.
- Good, R. 1953. **Geography of flowering plants.** Longmans & Co., London.
- Godall, D.W. 1966a. **A new similarity index based on probabilities.** Biometrics, 22:888-907.
- Godall, D.W. 1966b. **Numerical taxonomy of bacteria - some published data re-examined.** J. Gen. Microbiol., 42:25-37.
- Goss, J.R. & Brooks, F.A. 1956. **Constants for empirical expressions for downcoming atmospheric radiation under cloudless skies.** J. Meteorol, 13:482-488.
- Gower, J.C. 1966. **Some distance properties of latent root and vector methods used in multivariate analysis.** Biometrika, 53:325-338.
- Gower, J.C. 1967. **A comparison of some methods of cluster analysis.** Biometrics, 23:623-628.

- Gower, J.C. 1971. **A general coefficient of similarity and some of its properties.** Biometrics, 27:857-871.
- Gower, J.C. & Ross, G.J.S. 1969. **Minimum spanning tree and single linkage cluster analysis.** Appl. Statist., 18:54-64.
- Gray, C.C. 1970. **An International upland crops program.** The Rockefeller Foundation, 48p.
- Greenland, D.J. 1977. **The magnitude and importance of the problem.** In Intern. Inst. Trop. Agric. Proc. Intern. Conf. on Soil conservation and management in humid tropics, Ibadan, Nigeria, pp.3-7.
- Griffiths, J.F. 1967. **Rainfall patterns within the tropics.** Proc. Third Intern. Biometeorol. Congress, Pau, S. France, S.W. Tromp & W.H. Weihe (Eds.), Oxford, Pergoman Press, Vol. 2.
- Griffiths, J.F. (Ed.) 1971. **Climates of Africa.** World Survey of Climatology, Vol. 10, Ed.-in-Chief Landsberg, H.E. Elsevier Publ. Comp., Amsterdam, 604p.
- Grindley, J. 1970. **Estimation and mapping of evaporation.** Proc. Symp. on World water balance, Vol. 1, 200p.
- Hashimi, F., Smith, G.W. & Habibian, M.T. 1981. **Inadequacies of climatological classification systems in agroclimatic analogue equations - suggested alternatives.** Agric. Meteorol., 24:157-173.
- Harbaugh, J.W. & Merriam, D.F. 1968. **Computer applications in strategraphic analysis.** John Wiley & Sons, Inc., London, pp.157-209.
- Hargreaves, G.H. 1971. **Precipitation, dependability and potential for agricultural production in northeast Brazil.** EMBRAPA and Utah State Univ. Publ. No. 74-D159, 123p.
- Hargreaves, G.H. 1973. **Monthly precipitation probabilities for northeast Brazil.** Utah State Univ. Contract AID/CSD 2167, Dept. Agric. Irrig. Engin. 123p.
- Hargreaves, G.H. 1974. **Climatic zoning for agricultural production in northeast Brazil.** Utah State Univ., USAID - Contract No. Aid/CSD 2167, 16p.

- Hargreaves, G.H. 1975. **Water requirements manual for irrigated crops and rainfed agriculture**. EMBRAPA and Utah State Univ., 74-D158. 40p.
- Hargreaves, G.H. 1977. **World water for agriculture [precipitation, probabilities, climate and moisture adequacy]**. Utah State Univ., Logan, Utah. 171p.
- Hiler, E.A. & Clark, R.N. 1971. **Stress day index to characterize effects of water stress on crop yields**. Trans. ASAE, 14:757-761.
- Hiler E.A. et al. 1974. **Irrigation timing by the stress day index method**. Trans. ASAE, 17:393-398.
- Hodson, F.R., Sneath, P.H.A. & Doran, J.E. 1966. **Some experiments in the numerical analysis of archeological data**. Biometrika, 53:311-324.
- Holdefliess, P. 1930. **Agrometeorologie: die Abhangkeiten der Enntertrage von wetter und klima**. Berlin, P. Parey, 107p.
- Hounam, C.E. 1965. **Comparison of evaporation from US class "A" pan. Australian standard tank and estimates selected**. Aust. Met. Mag., 49:1-13.
- Hubble, G.D. 1972. **The swelling clay soils**. In Proc. Symp. on Physical Aspects of Swelling Clay soils. B.F.J. James (Ed.), University of New England, Armidale, New South Wales, pp.1-11.
- Huda, A.K.H. *Agroclimatology Annual Report - 1980-81. ICRISAT, India*
- Hult, R. 1892. **Forsok till en endelning of joryton after khimatiske greender venteneskapliga meddelenden of geografiska sorenin**. Finland, 1(1892-1893).
- ICAR 1982. **A decade of dry-land agricultural research in India 1971-80**. All India Co-ordinated Research Project for dry-land agriculture (AICRPDA). Saidabad, Hyderabad, India. 252p.
- ICRISAT 1981. **Improving the management of India's deep black soils**. Sponsored by Indian Ministry of Agriculture/ICAR/ICRISAT. ICRISAT Patancheru P.O., A.P., India. 106p.
- IMD (Undated). **Climatological tables of observations in India [1931-1960]**. India Meteorological Dept., Poona (India), 470p.

- IMD 1967. **Monthly rainfall and rainy days for 1901-1950.** India Meteorological Dept., Poona (India).
- Ivimey-Cook, R.B. 1969. **The phenetic relationships between species of ononis.** In Proc. Numerical Taxonomy, A.J. Cole (Ed.), Academic Press, London, pp.69-90.
- Jensen, M.E. 1968. **Water consumption by agricultural plants.** In T.T. Kozlorsvoski (Ed.), Water deficits and plant growth, Vol. II. Academic Press, Inc., New York, pp.1-22.
- Jensen, M.E., Wright, J.L. & Pratt, B.J. 1971. **Estimating soil moisture depletion from climate, crop and soil data.** Trans. ASAE, 14:954-959.
- Johnson, B.L.C. 1979. **India: Resources and development.** Heinmann Educational Books, London.
- Jones, M.J. & Wild, A. 1975. **Soils of the west African Savanna, the maintenance and improvement of their fertility.** Commonw. Buru. Soils. Tech. Commun., 55, Harpendan, England.
- Kanwar, J.S. 1975. **Forward to 'Physical aspects of Dry-land Farming'.** U.S. Gupta, (Ed.), Oxford and IBH Publ. Co., New Delhi.
- Kanwar, J.S. 1979. **Research at ICRISAT - an overview.** In Proc. of the Intern. Symp. on The development and transfer of technology, ICRISAT Patancheru P.O., A.P., India, pp.5-10.
- Kampen, J. 1976. **Some thoughts on the conservation, development and use of land and water resources in drought prone areas.** Presented at training program for agricultural officers from selected DPAP districts, ICRISAT, Hyderabad, India.
- Kampen J. et al. 1975. **Soil and water conservation and management in farming systems research for semi-arid tropics.** In Proc. of the Intern. Workshop on Farming Systems, ICRISAT, Hyderabad, India, pp.3-43.
- Kampen, J. & Burford, J.R. 1979. **Production systems soil related constraints and potentials in the semi-arid tropics with special reference to India.** Paper presented in the seminar held at IRRI, June 1979.



- Kassam, A.H. 1976. **Crops of the west African semi-arid tropics.** ICRISAT, Hyderabad, India.
- Koppen, W. 1936. **Das Geographische System der Klimate.** In Handbuche der Klimatologie, Vol. I, Part C, W. Koppen and R. Giner (Eds.), Gerbrender Borntrager, Berlin.
- Krantz, B.A. 1979. **Intercropping on an operational scale in an improved farming systems.** In Proc. Intern. Workshop on Intercropping, ICRISAT Patancheru P.O., A.P., India, pp.318-327.
- Krantz, B.A. & Russell, M.B. 1971. **Avenues for increased wheat production under Balani condition.** Presented at wheat symposium, U.P. Agricultural University, Pantnagar, U.P., India.
- Krishnan, A. 1975. **Some climatological features of the simi-arid tropical regions of the world.** Proc. Intern. Workshop on Farming Systems, ICRISAT, Hyderabad, India, pp.53-124.
- Lance, G.N. & Williams, W.T. 1966. **A generalized sorting strategy for computer classification.** Nature (London), 212:218.
- Lance, G.N. & Williams, W.T. 1967a. **Mixed-data classification programs. I. Agglomerative systems.** Aust. Comput. J., 1:15-20.
- Lance, G.N. & Williams, W.T. 1967b. **A general theory of classificatory sorting strategies. I. Hierarchical systems.** Comput. J., 9:373-380.
- Landsburg, H.E. et al. 1963. **World Maps of climatology.** Springer, Berlin, 5 Maps, 28p.
- Lenington, R.K. & Flake, R.H. 1974. **Statistical evaluation of a family of clustering methods.** Proc. 8 Intern. Conf. on Numerical Taxonomy (Deiras, Portugal), G.F. Establook (Ed.), W.H. Freeman & Co., San Fransisco, pp.1-37.
- Lima, A.F. & Quiraz, M.A. de 1981. **Guidellnes for an intercropping research program in northeast Brazil<Forthcomming>.**
- Ling, R.F. 1971. **Cluster analysis.** Unpublished Ph.D. dissertation, Department of Statistics, Yale University.
- Liu, W.T. 1977. **Comparison of crop-climatic environment for four**

**locations in the northeast Brazil. ICRISAT Patancheru P.O., A.P., India. 109p.**

- Mafra, R.C. et al. 1979. Studies on the intercropping of sorghum and corn with phaseolus beans [Phaseolus Vulgaris] and cowpea [Vigna Unguiculata]. In Proc. Intern. Workshop on Intercropping. ICRISAT Patancheru P.O., A.P., India. pp.46-51.**
- Mather, J.R. 1978. The climatic water budget in environmental analysis. Lexington books, D.C. Heath & Co., Lexington, Massachusetts, Toronto.**
- Mayer, E., Linsley, E.G. & Usinger, R.L. 1953. Methods and principles of systematic zoology. McGraw-Hill, New York.**
- McCown, R.L. 1981a. The climatic potential for beef cattle production in tropical Australia: Part I - simulating the annual cycle of liveweight change. Agric. Syst., 6:303-317.**
- McCown, R.L. 1981b. The climatic potential: Part III - variation in the commencement, cessation and duration of the green season. Agric. Syst., 7:163-178.**
- McCulloch, J.S.G. 1965. Tables for the rapid computation of the Penman estimate of evaporation. East African Agric. & Forestry J., XXX:286-295.**
- McQuitty, L.L. 1964. Capabilities and improvements of linkage analysis as a clustering method. Educ. Psychol. Measure., 24:441-456.**
- McQuitty, L.L. 1966. Similarity analysis by reciprocal pairs for discrete and continuous data. Educ. Psychol. Measure., 26:825-831.**
- McQuitty, L.L. 1967. Expansion of similarity analysis by reciprocal pairs for discrete and continuous data. Educ. Psychol. Measure., 27:253-255.**
- MD 1971. Climatological data of Thailand [25 year period, 1951-1975]. Meteorological Dept., Ministry of Comm., Bangkok, Thailand.**
- Meher-Homji, V.J. 1962. Phytogeographical studies of the semi-arid regions of India. Ph.D. Thesis, Bombay Univ., Bombay.**

- Minhas, B.S., Parikh, K.S. & Srinivasan, T.N. 1974. **Towards the structure of a production function for wheat yields with dated inputs of irrigated water.** *Water Resources Res.*, 10:383-393.
- Mohsin, M.A. & Sinha, N.P. 1979. **Rainfed agricultural technology for Bihar.** Presented at kharif workshop of the Dept of Agric., Patna, India, 16p.
- Monteith, J.L. 1959. **The reflection of short wave radiation by vegetation.** *Quart. J. Roy. Met. Soc.*, 85:386-392.
- Moore, R.M. 1970. **Australian grasslands.** In *Australian Grasslands*, R.M. Moore (Ed.), Aust. Nat. Univ. Press, Canberra, pp.85-100.
- Moore, A.W. & Russell, J.S. 1967. **Comparison of coefficients and grouping procedures with numerical analysis of soil trace elements data.** *Geoderma*, 1:139-158.
- Morgan, W.B. & Pugh, J.C. 1969. **West Africa.** Methuen, London.
- Murthy, R.S. & Pandey, S. 1978. **Delineation of agroclimatological regions of India.** In *Proc. Comm. V. 11th congress of the Intern. Soc. Soil Sci.*, Edmonton, Canada.
- Nix, H.A. 1968. **The assessment of biological productivity.** In *Land Evaluation*, G.A. Stewart (Ed.), Melbourne, McMillan, pp.77-87.
- Nix, H.A. 1975. **The Australian climate and its effects on grain yield and quality.** In *Australian Field crops I: wheat and other temperate cereals*, Alex Lazenby & E.M. Matheson (Eds.), pp.183-226.
- Nix, H.A. 1978. **Availability of land for energy cropping in Australia.** In *Alcohol Fuels*, Sydney, Vol. 6, pp.5-10.
- Nix, H.A. 1979. **Agroclimatic analogues in transfer of technology.** In *Proc. Intern. Symp. on Development and Transfer of Technology for Rainfed Agriculture and the SAT Farmer*, ICRISAT Patancheru P.O., A.P., India, pp.83-88.
- Nix, H.A. 1981. **Simplified simulation models based on specified minimum data sets: the CROPEVAL concept.** In *Application of Remote Sensing for Agricultural Production Forecasting*, A. Berg (Ed.), A.A. Balkema, Rotterdam, pp.151-169.

- Nix, H.A. & Fitzpatrick, E.A. 1969. **An index of crop water stress related to wheat and grain sorghum yields.** *Agric. Meteorol.*, 6:321-337.
- Norman, D.W. 1975. **Rationalization of mixed cropping under indigeneous condition: the example of northern Nigeria.** Bull. No. 232, Institute for Agricultural Research, Samaru, Nigeria. 24p.
- Nye, P.H. & Greenland, D.J. 1960. **The soil under shifting cultivation.** *Commonw. Buru. Soils. Tech. Commun.*, 51, Harpenden, England.
- Orloci, L. 1967. **An agglomerative method for classification of plant communities.** *J. Ecol.*, 55:193-206.
- Papadakis, J. 1975. **Climates of the world and their agricultural potentialities.** Cordoba, Spain, Papadakis.
- Parthasarathy, B. & Dhar, O.N. 1974. **Trend analysis of annual Indian rainfall.** *Hydrol. Sci. Bull.*, 20:257-260.
- Parthasarathy, B. & Dhar, O.N. 1978. **Climatic fluctuations over Indian region-Rainfall: A review.** IITM, Res. Rep. No. 025, Poona, India.
- Patrick, G.F. 1972. **Development of agriculture in northeastern Brazil.** Relatoria de pesquisa no. 11, IPEA/INPES Recife, Brazil.
- Penman, H.L. 1948. **Natural evaporation from open water, bare soil and grass.** *Proc. Roy. Soc. London (A)*, 193:120-146.
- Prim, R.C. 1957. **Shortest connection networks and some generalizations.** *Bull. System. Tech. J.*, 36:1389-1401.
- Raman, C.R.V. & Murthy, B.S. 1971. **Water availability periods for crop planning.** *Sci. Rept.*, No. 173, IMD, Poona, India.
- Rao, K.N., George, C.J. & Ramasastry, K.S. 1971. **Potential evapotranspiration over India.** *Sci. Rep. No. 136*, IMD, Poona, India.
- Rao, K.N., George, C.J. & Abhyankar, V.P. 1972a. **Nature of the frequency distribution of Indian rainfall: Monsoon and annual.** *Indian J. Meteorol. Geophys.*, 23:507-514.

- Rao, K.N., Jayanthi, S. & Bhargava, V.K. 1972b. **Indian monsoon correlations -Part I: Monthly interrelation for all the Meteorological sub-divisions of India.** Met. Monograph. No.4. IMD, New Delhi, India.
- Rao, M.R. & Natarajan, M. 1981. **Traditional cropping systems and some experimental results in the semi-arid tropics of Africa, Brazil, and Thailand.** In Proc. Summer Institute on Production Physiology of dry-land crops, APAU/ICAR, Rajendranagar, Hyderabad, India.
- Rao, M.R. & Willey, R.W. 1980. **Evaluation of yield stability in intercropping: studies on sorghum/pigeonpea.** Exper. Agric., 16:105-116.
- Reddy, S.J. 1971a. **An empirical method for the estimation of total solar radiation.** Solar Energy [USA], 13:289-290.
- Reddy, S.J. 1971b. **An empirical method for the estimation of net radiation intensity.** Solar Energy [USA], 13:291-292.
- Reddy, S.J. 1973. **An empirical method for estimation of sunshine from total cloud amount.** Solar Energy [USA], 15:281-285.
- Reddy, S.J. 1975. **Dates of onset and withdrawal and their association to rainfall over different sub-divisions in India.** Unpublished Report, IMD, Poona, India.
- Reddy, S.J. 1977a. **A review-agroclimatic classification.** ICRISAT Patancheru P.O., A.P., India, 41p.
- Reddy, S.J. 1977b. **Empirical method of estimation of water balance.** Proc. Nat. Sci. Acad., 43B:1-5.
- Reddy, S.J. 1979a. **User's manual for water balance models.** ICRISAT Patancheru P.O., A.P., India, 28p.
- Reddy, S.J. 1979b. **Modelling water balance: approaches and applications.** Int. Symp. on Effects of weather on agricultural production, Univ. Kalyan, Kalyan, W.B., India.
- Reddy, S.J. 1979c. **A review-measurements and estimation of evaporation and evapotranspiration.** ICRISAT Patancheru P.O., A.P., India.
- Reddy, S.J. 1980. **Rainfall distribution over ICRISAT Centre.** ICRISAT Patancheru P.O., A.P., India.

- Reddy, S.J. 1981a. **Potential evapotranspiration estimates in the NE Brazil.** ICRISAT Patancheru P.O., A.P., India.
- Reddy, S.J. 1981b. **Potential evapotranspiration estimates in the Thailand.** ICRISAT Patancheru P.O., A.P., India.
- Reddy, S.J. 1981c. **Estimation of global solar radiation.** Solar Energy [USA], 26:279.
- Reddy, S.J. 1983a. **A simple method of estimating the soil water balance.** Agric. Meteorol., 28:1-17.
- Reddy, S.J. 1983b. **Irrigation scheduling using ICSWAB model.** Pesq. Agropec. Bras., Brasilia, 18:1121-1126.
- Reddy, S.J. 1984. **Climatic fluctuations and homogenization of northeast Brazil using precipitation data.** Pesq. Agropec. Bras., Brasilia, 19:529-543.
- Reddy, S.J. & Rao, K.R. 1973. **An empirical method for the estimation of evaporation from the free surface of water.** Indian J. Meteorol. Geophys., 24:137-152.
- Reddy, S.J. & Reddy, R.S. 1973. **A new method of estimation of water balance.** Proc. Int. Trop. Meteorol. Meeting, [Amer. Met. Soc.], Nairobi, Kenya, pp.277-280.
- Reddy, S.J. & Rao, K.R. 1976. **Radiation and evaporation distribution over India.** Nat. Geogr. J. India, XXII:54-63.
- Reddy, S.J. & Virmani, S.M. 1980a. **Potential evapotranspiration estimates in the semi-arid west African region.** ICRISAT Departmental Progress Report (Agroclimatology No. 3), ICRISAT Patancheru P.O., A.P., India.
- Reddy, S.J. & Virmani, S.M. 1980b. **Pigeonpea and its climatic environment.** In Proc. Intern. Workshop on Pigeonpea, ICRISAT/ICAR, ICRISAT Patancheru P.O., A.P., India, pp.259-270.
- Reddy, S.J. & Singh, S. 1981. **Climate and soils of the semi-arid tropical regions of the world.** In Proc. Summer Institute on Production Physiology of Dry-land Crops, APAU/ICAR, Rajendranagar, Hyderabad, A.P., India.
- Reddy, S.J. & Virmani, S.M. 1982. **Grouping of climates of India and west Africa: using principal component analysis.**

ICRISAT. FSRP. Agroclimatology Annual Report 1980-81. Progress Report No. 5. ICRISAT Patancheru P.O., A.P., India. pp.21-25.

Reddy, S.J. & Amorim, N.M. da S. 1984. **A method for the estimation of potential evapotranspiration and/or open pan evaporation over Brazil.** Pesq. Agropec. Bras., Brasilia. 19:247-267.

Reddy, S.J., Sivakumar, M.V.K. & Virmani, S.M. 1977. **An analysis of the agricultural climate of Dharwar [Karnataka] district.** Seminar on Soil and Water conservation in black soils. Inst. Agric. Tech. Dharwar, India. 14p.

Reddy, S.J., Rao, M.R. & Willey, R.W. 1982. **Identification of cropping patterns at few selected locations in India: Soil water balance simulation.** Under preparation.

Reddy, S.J., Maiti, R.K. & Seetharama, N. 1984a. **An iterative regression approach for prediction of sorghum (sorghum bicolor) phenology in the semi-arid tropics.** Agric. For. Meteorol., 32:323-338.

Reddy, S.J., Amorim, N.M. da S. & Elpidio, M. da G. da S. 1984b. **A simple method for the estimation of global solar radiation over northeast Brazil.** Pesq. Agropec. Bras., Brasilia. 19:391-405.

Reid, R., Ryan, D.M. & Burt, R.L. 1976. Exploration for and utilization of collections of tropical pasture legumes. II The Papadakis system of climatic classification applied to testing areas in northern Australia. Agro-ecosyst., 2:309-318.

Ritchie, J.T. 1972. **Model for predicting evaporation from a row crop with incomplete cover.** Water Resources Res., 8:1204-1213.

Robertson, G.W. 1976. **Dry and wet spells.** UNDP/FAO. Tun Razak Agric. Res. Center, Sungh: Teskam, Malaysia. Project Field Report, Agrometeorology: A-6.

Rohlf, F.J. 1974. **Methods of comparing classifications.** Ann. Rev. Ecology & Systematics, 14:101-113.

Ross, G.J.S. 1969. **Classification techniques for large sets of data.** In proc. Numerical Taxonomy. A. J. Cole (Ed.), Academic Press, London. pp.224-233.

- Russell, J.S. 1978. **Classification of climate and potential usefulness of pattern-analysis techniques in agroclimatology research.** In Proc. Agroclimatological research needs of the semi-arid tropics. ICRISAT Patancheru P.O., A.P., India. pp.47-58.
- Russell, J.S. & Moore, A.W. 1976. **Classification of climate by pattern analysis with Australian and south African data as an example.** Agric. Meteorol., 16:45-70.
- Ruthenberg, H. 1971. **Farming systems in the tropics.** Clarendon Press, Oxford.
- Ruthenberg, H. 1974. **From shifting cultivation to semi-permanent and permanent farming in the African Savannas.** In Proc. Intern. Workshop on Farming Systems, ICRISAT, Hyderabad, India. pp.325-350.
- Ryan, J.G. et al. 1975. **Socio-economic aspects of agricultural development in the semi-arid tropics.** Proc. Intern. Workshop on Farming Systems, ICRISAT, Hyderabad, India. pp.389-431.
- Ryan J.G. et al. 1982. **Assessing the economics of water harvesting and supplemental irrigation: A simulation approach.** ICRISAT Patancheru P.O., A.P., India (Draft).
- Sanchez, P.A. 1976. **Properties and management of soils in the tropics.** John Willey, New York. 618p.
- Schreiber, D. 1975. **Entwurf Einer Klimarinteilung fur land wirt schaprlliche Balance.** Bochemmer Geographische Arbeiten, Paderborn.
- Saleaninov, G.T. 1937. **Mirovoi agroclimaticheskii. Sprovochnik [World agroclimatic guide.].**
- Sharma, R.P.R., Thakur, H.C. & Sharma, H.M. 1980. **Pigeonpea as a labi crop in India. Workshop on pigeonpea, vol.I, pp.26-36, ICRISAT, Patancheru, India.**
- Simpson, G.G. 1961. **Principles of animal taxonomy.** Columbia Univ. Press. New York.
- Singh, J. 1974. **Agricultural Atlas of India: A geographical analysis.** Krukshetra. Vishal, India.
- Singh, R.P., Singh, A. & Ramakrishna, Y.S. 1974. **Cropping patterns for dry-lands of India: An agroclimatic approach.** Annals of Arid Zone, 13:145-164.



- Slatyer, R. 1967. **Plant-water relationship**. Academic Press, New York.
- Slatyer, R. 1975. **Further trends in agroclimatology**. In Proc. of the Reading Symp. on Agroclimatological needs, Natural Resources Res. No. 7, UNESCO, pp.367-389.
- Smith, G.D., Yule, D.F. & Coughland, K.J. 1983. **Soil physical factors in crop production on vertisols in Queensland, Australia**. Proc. Intern. Workshop on Soils (Research to Resolve Selected Problems of soils in the tropics), ACIAR/IBSRAM, 12-16 September 1983, Townsville, Queensland, Australia, pp.87-104.
- Smith, J.W. 1920. **Agricultural meteorology: The effect of weather and crops**. McMillan, New York, 304p.
- Smith, R.W. 1976. **Numerical analysis of ecological survey of data**. Ph.D. Thesis, Univ. Southern California.
- Sneath, P.H.A. & Sokal, R.R. 1973. **Numerical Taxonomy**. Freeman Press, San Francisco.
- Sokal, R.R. 1974. **Classification, purpose, principles, progress, prospects: clustering and other new techniques have changed classificatory principles and practices in many sciences**. Science, 165:1115-1123.
- Sokal, R.R. & Mitchener, C.D. 1958. **A statistical method for evaluating systematic relationships**. Kans. Univ. Sci. Bull. No. 38:1409-1438.
- Sokal, R.R. & Rohlf, F.J. 1962. **The comparison of dendrograms by objective methods**. Taxon., 11:33-40.
- Sokal, R.R. & Sneath, P.H.A. 1963. **Principles of numerical taxonomy**. Freeman & Co., London.
- Sorensen, T. 1948. **A method of establishing groups of equal amplitude plant sociology based on similarity of species content and its application to analysis of the vegetation on Danish commons**. Biol. Skr., 5:1-12.
- Spratt, D. & Choudhury, S.L. 1978. **Improved cropping systems for rainfed agriculture in India**. Field Crops Res., 1:103-126.
- Supan, A. 1884. **Greendzuges der physischen Erdkunde**. Leipzig und spatere anlagen.

- Stoop, W.A. & Pattanayak, C.M. 1979. **The ICRISAT Cooperative program in Upper Volta.** In Proc. on The development and transfer of technology to rainfed agriculture and the SAT farmer, ICRISAT Patancheru P.O., A.P., India, pp.143-150.
- Swindale, L.D. 1979. **Problems and concepts of agrotechnology transfer within the tropics.** In Proc. on The development and transfer of technology for rainfed agriculture and the SAT farmer, ICRISAT Patancheru P.O., A.P., India, pp.73-82.
- Swindale, L.D. 1982. **Distribution of and use of arable soils in the semi-arid tropics.** In Proc. on Managing soil resources to meet the challenges to mankind, ISSS/AISS/IBG, 12 ICSS, New Delhi, India, pp.67-100.
- Theile, P. 1895. **Deutschulands, landwirtscha ftliche klimatographic.** Bosn.
- Thom, A.S. & Oliver, H.R. 1977. **On Penman's equation for estimating regional evaporation.** Quart. J. Roy. Met. Soc., 103:345-347.
- Thompson, B. 1965. **The climate of Africa.** Oxford University Press, London, 132p.
- Thornthwaite, C.W. 1948. **An approach towards a rational classification of climate.** Geogr. Rev., 38:55-64.
- Thornthwaite, C.W. & Mather, J.R. 1955. **The water budget and its use in irrigation.** In Water-the Yearbook of Agriculture, Washington D.C., USDA, 346p.
- Troll, C. 1965. **Seasonal climates of the earth.** In World Maps of Climatology, E. Rodenwaldt and H. Juszat (Eds.), Berlin, Springer-Verlag, 28p.
- Turkey, J.W. 1954. **Unsolved problems of experimental statistics.** J. Am. Stat. Ass., 49:706-731.
- Tyson, P.D. 1978. **Rainfall changes over Southern Africa during the period of meteorological record.** In Biogeography and Ecology of Southern Africa, M.J.W. Werger (Ed.), Dr. W. Junk b.v. Publishers, The Hague.
- Van Bavel, C.H.M. 1966. **Combination [Penman type] methods.** Proc. Evapotranspiration and its role in water resources management, Am. Soc. Agric. Eng.

- Virmani, S.M., Reddy, S.J. & Bose, M.N.S. 1980. **A handbook on the rainfall climatology of west Africa: Data collection for selected locations.** ICRISAT Information Bull. No. 7, ICRISAT Patancheru P.O., A.P., India. 52p.
- Walter, H., Hernickell, E. & Mueller-Dombois, D. 1975. **Klimadiagrammkarten.** Vegetations Monographien der einzelnen grotanme. Band X. Gustav Fischer Verlag, Strettgart.
- Ward, J.H. 1963. Hierarchical grouping to optimizing an objective function. J. Amer. Stat. Ass., 58:236-244.
- Waring, S.A., Fox, W.E. & Teakle, L.J.H. 1958. Fertility investigations on the black earth wheatlands of the Darling Downs, Queensland. II. Moisture and evapotranspiration in relation to the wheat crop. Aust. J. Agric. Res., 9:717-729.
- Webster, R. 1979. Quantitative and numerical methods in soil classification and survey. Monographs on soil survey, Clarendon Press, Oxford.
- Weston, E.J. et al. 1981. Assessment of the agricultural and pastoral potential of Queensland. Tech. Report No. 27, Agricultural Branch, Department of Primary Industries, Brisbane.
- Williams, W.T. 1971. Principles of clustering. Annu. Rev. Ecol. Sys., 2:303-326.
- Williams, W.T. 1976a. Hierarchical agglomerative strategies. In Pattern analysis in agricultural Science, W.T. Williams (Ed.), CSIRO, Melbourne, Elsevier, 331p.
- Williams, W.T. 1976b. Attributes. In Pattern analysis in agricultural Science, W.T. Williams (Ed.), CSIRO, Melbourne, Elsevier, 331p.
- Williams, W.T. & Lance, G.N. 1969. Application of computer classification techniques to problems in land survey. Bull. Inst. Statist., 42:345-355.
- Williams, W.T., Clifford, H.D. & Lance, G.N. 1971. Group size dependence: a rationale for choice between numerical classifications. Computer J., 14:157-162.
- Willimolt, C.J.A. 1977. A component analytic approach to precipitation

**regionalization in California.** Arch. Met. Geophys. Biokl. Ser. B., 24:269-281.

Willimolt, C.J.A. 1978. **P-mode principal component analysis grouping and precipitation regions in California.** Arch. Met. Geophys. Biokl. Ser. B., 26:277-295.

Wilsie, C.P. & Shaw, R.H. 1954. **Crop adoption and climate.** Adv. Agron., VI:199-252.

Wishart, D. 1969. **An algorithm for hierarchical classifications.** Biometrics., 25:165-170.

WMO 1971. **Climatological normals [clino] for climate and climateship stations for the period 1931-1960.** WMO/OMM-No. 117, TP.52. Geneva, Switzerland.

Appendix A : Climatic classification procedures.

	Moisture parameters				
	Monthly dependable rainfall	Actual evapotranspiration	Mean monthly rainfall + stored soil moisture	Mean monthly rainfall	Mean annual rainfall
Evaporative demand parameter				xStefanoff(1930), xThomas (1932), x Walter (cf. Moreau, 1938), xaubrevelle (1949), xCruietzbere(1950), xBagnauls & Gauszen (1953, 1957), xGauszen(1955), Troll(1965) *	Koppen(1900, 1918, 1931, 1936 *), Herbertson(1905), deMartonne (1908, 1926), Lang(1920), Emberger(1930, 1955), Champion (1945), Popov (1948), Shanbhag (1956), Walter et al. (1960), Menor-Homji (1963, 1965), Schreiber(1975) *
Temperature					Budyko (1956) * Mangenot (1951) Szymickwicz (1925), Meyer (1926), Prescott(1934, 1938, 1943), Trumble (1937), Hosking(1937), Capot-Key (1951) Transeau(1905), Penck(1910), Ivanov(1948), Prescott(1949, 1956, 1965), Bharucha & Shanbhag (1957)
Net Radiation					
Relative Humidity					
Saturation deficit					
Evaporation					
Potential evapo-transpiration	xHargreaves (1971) *	xEagleman (1976) *	Thornthwaite (1931, 1933, 1948, 1951), Thornthwaite & Mather (1955) *	Reddy(1977a) *	Reddy & Reddy (1973) *

Note: ' x ' before the reference represents the methods under duration of moist or dry period and the rest under the annual index.  
Except the references with \* are given in Appendix B.

## Appendix B : Secondary references.

Author(s)	Year	Reference	Author(s)	Year	Reference
Aubreville, A.	1949	Climates, forests et desertification de l'Afrique tropicale, Paris: Societe d'editions Geographiques, Maritimes et Coloniales.	Lang, R.	1920	Verwitterung und bodenbildung als einfuhrung in die bodenkunde. Stuttgart:Schweizerische verlagsbuchandlung, pp.123.
Bagnouls, F. & Gaussem, H.	1953	Saison seche et regime xerothermique. Documents pour les caters des productions vegetales, Toulouse, 3,1.	Mangenot, G.	1951	Revue Generale de Botanique, 58,353.
"	1957	Annales de Geographie, 355,193.	Meher-Homji, V.M.	1963	Tropical Ecology, 5,17.
Bharucha, F. R. & Shanbhag, G.Y.	1957	Botanical memoirs No.3, Univ. of Bombay.	"	1965	Annals of Arid Zone, 4,152.
Capot-Rey, R.	1951	Bulletin de l'Association de Geographes Français, pp.73.	Meyer, A.	1926	Chemie du Erde, 2,209.
Champion, H.G.	1936	Indian Forest Records (H.S., 1).	Moreau, R.E.	1938	J. Geol., 26,467.
Creutzberff, H.	1950	Petermanns. Geogr. Mitt., 94,57.	Penck, A.	1910	Sitz. ber. Preuss. Akad. Wiss. Physikmath. Kl., pp.236.
Cure, P.	1945	Documents pour les Cartes des production vegetales, Ser. Gener. T.3.1, Art.3.	Popov, V.I.	1948	Sci. Repbl. State Univ. Kiev., 7(1).
de Martonne, E.	1908	Traite de Geographie physique 7th ed., 1948, Paris.	Prescott, J.A.	1934	Trans. Roy. Soc. S. Austr., 58,48.
"	1926	Compt. rend., 182,1395.	"	1938	" " " " 62,229.
Emberger, L.	1930	Revue Generale de botanique, 42,641 & 705.	"	1943	British Commonwealth Specialist Conf. Agric., Adelaide.
"	1955	Recueil des travaux des laboratoires des botanique, Geologie et zoologie de la faculte des sci. de l'Universite de Montpellier (Series botanique No. 7), 3.	"	1949	Proc. UNESCO Symp. Arid Zone Climatology, Canberra.
Gaussem, H.	1955	Les climats analogues a l'echelle du monde. Comptes Rendus. Hebdomadaires des Seances de l'Academie d'Agriculture de France, Vol.41.	"	1956	Trans. Roy. Soc. S. Austr., 89,5.
Herberton, A.J.	1905	Geographical J., 25,300.	Shanbhag, G.Y.	1956	Indian Geogr. J., 31,20.
Hosking, J.S.	1937	Current Sci., 422.	Stefanoff, B.	1930	Зbornik na bulgarskata akademiya na naukite, 26.
Ivanov, N.N.	1948	Proc. Soviet Geogr. Cong. Vol.1, Acad Sci., USSR.	Szymirkwicz, D.	1925	Acta. Soc. Botan. Polon., 2,239.
Koppen, W.	1900	Geographische Zeitschrift, 6,593 & 657.	Thomas, A.S.	1932	J. Geol., 20,263.
"	1918	Petermanns Geographische Mitt., 64,193 & 243.	Thornthwaite, C.W.	1931	Geogr. Rev., 21,633.
"	1931	Grundriss du Klimakunde, Walter de Gruyter, Berlin.	"	1933	" " 23,433.
			"	1943	" " 33,233.
			Transeau, E.N.	1905	Bull. Amer. Meteorol. Soc., 32,166.
			"	1951	Amer. Naturalist, 39,875.
			Trumble, H.C.	1937	Trans. Roy. Soc. S. Austr., 61,41.
			"	1939	" " 63,36.
			Walter, H., Leith, H. & Renger, H.	1960	Klimadiagramm. Weltatlas Jena.

## Appendix C : The standard weeks.

<u>Week No.</u>	<u>Month</u>	<u>Dates</u>	<u>Week No.</u>	<u>Month</u>	<u>Dates</u>
1	January	1-7	27	July	2-8
2		8-14	28		9-15
3		15-21	29		16-22
4		22-28	30		23-30*
5		29-4	31		31-6
6	February	5-11	32	August	7-13
7		12-18	33		14-20
8		19-25	34		21-27
9		26-4@	35		28-3
10	March	5-11	36	September	4-10
11		12-18	37		11-17
12		19-25	38		18-24
13		26-1	39		25-1
14	April	2-8	40	October	2-8
15		9-15	41		9-15
16		16-22	42		16-22
17		23-29	43		23-29
18		30-6	44		30-5
19	May	7-13	45	November	6-12
20		14-20	46		13-19
21		21-27	47		20-26
22		28-3	48		27-3
23	June	4-10	49	December	4-10
24		11-17	50		11-17
25		18-24	51		18-24
26		25-1	52		25-31

@ In leap year the week no. 9 will be 26 February to 4 March, i.e. 8 days instead of 7.

\* Week no. 30 will have 8 days (southern hemisphere)--in the case of northern hemisphere, week 30 will have 7 days and week 52 have 8 days and accordingly the dates from week 30 to 52 will change i.e. week 30 (July 23-29), week 31 (July 30-5), ..., week 52 (December 24-31).

Appendix D : List of rainfall stations for which the analysis was made.

S.No.	Station	Code	Lat.	Long.	Data base (Years)	S.No.	Station	Code	Lat.	Long.	Data base (Years)
			o ' "	o ' "					o ' "	o ' "	
A. INDIA											
1	Agra	AGR	27 10	78 02	27	2	Ahmednagar	AHG	19 05	74 55	69
3	Ajmer	AJM	26 27	74 37	30	4	Akola	AKL	20 42	77 02	30
5	Amrali	AMR	21 36	71 13	29	6	Amritsar	AMT	31 38	74 52	29
7	Anand	AND	22 34	73 01	50	8	Anatapur	ANT	14 41	77 37	59
9	Arogyavaram	ARG	13 52	78 30	17	10	Aurangabad	ARB	19 53	75 20	70
11	Banaras	BNR	25 18	83 01	27	12	Bangalore	BNG	12 58	77 35	70
13	Banswara	BNW	23 33	74 27	65	14	Barielly	BRL	15 09	76 51	68
15	Belgaum	BLG	15 51	74 42	73	16	Bellary	BLR	15 09	76 51	58
17	Bhir	BIR	19 00	75 46	70	18	Bhuj	BHJ	23 15	69 48	66
19	Bijapur	BJP	16 49	75 43	67	20	Bikaner	BKR	28 00	73 18	27
21	Chitradurga	CHT	16 14	76 26	69	22	Chittoor	CHR	13 13	79 07	20
23	Coimbatore	CMB	11 00	76 58	70	24	Cuddapah	CDP	14 29	78 50	70
25	Daltonganj	DTG	24 23	84 04	54	26	Deesa	DSA	24 12	72 12	69
27	Dhar	DHR	22 36	75 18	64	28	Dharmapuri	DHP	12 08	78 10	69
29	Dharwar	DHW	15 27	75 30	70	30	Dohad	DHD	22 50	74 16	37
31	Dungarpur	DGP	23 51	73 43	67	32	Gogha	GGH	21 41	71 17	66
33	Goarakhpur	GRK	26 45	83 42	66	34	Gulbarga	GLB	17 21	76 51	70
35	Hissar	HSR	29 10	75 44	63	36	Hyderabad	HYD	17 27	78 28	69
37	Indore	IND	22 43	75 48	60	38	Jabalpur	JBP	23 10	79 57	69
39	Jaipur	JPR	26 49	75 48	19	40	Jalgaon	JLG	21 03	75 34	69
41	Jhabua	JBA	22 47	74 35	68	42	Jodhpur	JDP	26 18	73 01	30
43	Jullunder	JLD	31 20	75 35	34	44	Kolar	KLR	13 08	78 08	69
45	Kota	KTA	25 11	75 51	25	46	Kurnool	KRN	15 50	78 04	70
47	Lucknow	LKN	26 45	80 53	67	48	Ludhiana	LDN	30 56	75 52	29
49	Madhurai	MDH	09 55	78 37	70	50	Mahboobnagar	MBN	16 44	77 59	70
51	Malegaon	MLG	20 33	74 32	70	52	Mandya	MND	12 32	76 53	70
53	Mysore	MSR	12 18	76 42	70	54	Manded	MND	19 08	77 20	58
55	Nasik	NSK	20 00	73 47	62	56	New Delhi	DLH	28 35	77 12	30
57	Ongole	ONG	15 34	80 03	31	58	Osmanabad	OSB	18 10	76 03	70
59	Padegaon	PDG	18 12	74 13	25	60	Pali	PLI	25 47	73 20	66
61	Palamau	PLM	24 03	84 34	68	62	Patan	PTN	24 13	84 11	30
63	Patiala	PTL	30 20	76 13	16	64	Phulbani	PHB	30 29	84 14	48
65	Poona	PNA	19 32	73 51	70	66	Rajkot	RJK	21 18	70 47	28
67	Raichur	PCR	16 12	77 21	62	68	Raipur	RPR	22 14	81 39	69
69	Ramanatnpuram	RMN	09 23	78 50	65	70	Ranchi	RNC	23 23	85 20	23
71	Rewa	RWA	24 32	81 15	31	72	Salem	SLM	11 39	78 10	69
73	Rongli	RGL	16 50	74 34	64	74	Satara	STR	17 41	73 59	40
75	Sholapur	SLP	17 40	75 54	51	76	Sikar	SKR	27 37	75 08	26
77	Tumkur	TMK	14 21	77 15	70	78	Udaipur	UDP	24 35	73 42	30
79	Vishakhapatnam	VIS	17 43	83 14	60	80	Jamalot	SKT			
B. UPPER VOLTA											
1	Aribinda	ARB	14 14	00 52	20	2	Bam(Tourcoing)	BAM	13 20	01 30	27
3	Banankeladaga	BNK	10 37	04 46	20	4	Banfora	BNF	10 37	04 46	48
5	Banfora Agric.	BNA	10 37	04 46	20	6	Bani	BNI	13 43	00 10	16
7	Batie	BTI	09 53	02 55	29	8	Eobo-Dioulasso	BOB	11 10	04 18	50
9	Bogande	BGN	12 59	00 08	25	10	Boromo	BRM	11 44	02 55	47
11	Boulsa	BLS	12 39	00 34	15	12	Dano	DAN	11 09	03 04	19
13	Dedougou	DDG	12 23	03 26	51	14	Diapaga	DPG	12 04	01 47	43
15	Diebougou	DBG	10 53	03 15	45	16	Dionkele	DNK	11 47	04 43	19
17	Djibo	DJB	14 06	01 37	21	18	Dori	DOR	14 02	00 02	45
19	Fada N Gourma	FIG	12 04	00 21	45	20	Parako Ba(Agro)	FRB	11 06	04 23	18
21	Gaoua	GAO	10 20	03 11	54	22	Garango	GRN	11 48	00 38	27
23	Gorgadji	GRD	14 02	00 31	10	24	Gorom-Gorom	GRM	14 27	00 14	17
25	Gourcy	GCR	13 12	02 21	17	26	Guilongou	GLG	12 37	01 18	15
27	Kamboince	KMB	12 28	01 33	17	28	Kampti	KMP	10 08	03 28	19
29	Kaya	KYA	13 06	01 05	52	30	Kommissiri	KBS	12 04	01 20	17
31	Koudougou	KDG	12 16	02 22	50	32	Koupela	KPL	12 11	00 21	49
33	Lantaogo	LTG	12 02	00 05	16	34	Leo	LEO	11 06	02 06	48
35	Manga	MNG	11 40	01 06	23	36	Markoye	MRY	14 38	00 04	17
37	Nasso	NSS	11 12	04 20	20	38	Niangoloko	NNG	10 16	04 55	22
39	Nouna	NNA	12 44	03 52	33	40	Grodara	ORD	10 59	04 55	18
41	Ouagadougou*MSNCDM		12 22	01 32	60	42	Ouahigouya	OHG	13 35	02 26	48
43	Ouargaye	ORG	11 32	00 01	15	44	Pabre	PBR	12 31	01 34	16
45	Pama	PAM	11 15	00 42	23	46	Po	PO	11 10	01 09	30
47	Saba	SBA	12 03	01 36	16	48	Sapone	SPN	12 03	01 36	16
49	Sebba	SEB	13 26	00 31	18	50	Segouenega	SGG	13 26	01 58	18
51	Sideradougou	SDR	10 41	04 15	18	52	Tenkodogo	TNK	11 45	00 23	48
53	Tougan	TGN	13 05	03 04	39	54	Tougouri	TGR	13 19	00 30	18
55	Yako	YAK	12 58	01 16	30	56	Zabre*	ZBR	11 10	00 39	19
57	Zorgho	ZRG	12 15	00 37	18	*Ouakadougou (Aero & Ville). Kantachari.					



C. SENEGAL

1	Bakel	BKL	14	54	12	28	49	2	Lambey Météo	BBM	14	42	16	28	46
3	Bignona	BGN	12	40	16	16	18	4	Boulet	BLL	14	17	15	32	16
5	Coki	CKI	15	31	16	00	26	6	Dagana	DGN	16	31	15	30	52
7	Dahra	DHR	15	20	15	29	37	8	Dakar Yoff	DKY	14	44	17	30	27
9	Daroumousty	DRM	15	02	16	02	23	10	Dialakoto	DLK	13	19	13	18	38
11	Diouloulou	DLL	13	02	16	30	29	12	Diourbel	DRB	14	39	16	14	52
13	Fatick	FTC	14	20	16	24	51	14	Foundiougne	FDG	14	07	16	28	42
15	Goudiry	GDR	14	11	12	43	30	16	Guento	GNT	13	33	13	49	34
17	Inhor	IHN	13	01	15	42	19	18	Joal	JAL	14	10	16	51	24
19	Kaffrine	KFN	10	06	15	33	38	20	Kaolack	KLK	14	08	16	04	53
21	Kebemer	KBR	15	22	16	27	21	22	Kedougou	KDU	12	34	12	13	47
23	Khombole	KML	14	46	16	42	18	24	Kidira	KDR	14	28	12	13	43
25	Kolda	KLD	12	53	14	58	48	26	Koumpentoum	KPT	13	59	14	33	27
27	Linguere	LGR	15	23	15	07	40	28	Louga	LGA	15	37	16	13	37
29	Maka-Couliben-tan	MKC	13	40	14	18	29	30	Matam	MTM	15	38	13	15	46
31	M Backe	MCK	14	48	15	55	35	32	M Bad-Thiaroye	MBT	14	46	17	29	44
33	M Boro	MBR	14	08	16	53	16	34	M Bour	MBU	14	25	16	58	37
35	Namary	NMR	15	02	13	34	19	36	Nioro du rip	NDR	13	44	15	47	36
37	Oussouye	OSY	12	29	16	32	32	38	Podor	PDR	16	38	14	56	48
39	Rufisque	RFS	14	44	17	18	16	40	Sadio	SDO	14	48	15	33	16
41	Sagata-Linguere	SLA	15	13	15	34	17	42	Sagata-Louga	SGO	15	17	16	11	16
43	Saint Louis	SLV	16	01	16	30	75	44	Saraya	SRY	12	47	11	47	28
45	Sedhou Ville	SDO	12	42	15	33	53	46	Sefa-Sedhiou	SSO	12	47	15	33	24
47	Tambacounda	TBC	13	46	13	41	48	48	Thiadiaye	TDY	14	25	16	42	22
49	Thimaka	TLK	15	02	16	15	18	50	Tivaouane	TVN	14	57	16	49	45
51	Velingara Casa mance	VLG	13	09	14	06	36	52	Ziguinchor	ZGR	12	33	16	16	50

\* Bambey Aero

@ Dakar (-Hospital; -Hann; -Cap Manual; &amp; -Goree)

\$ Saint Louis Aero

D. TROPICAL AUSTRALIA

1	Adelaide River	ADR	13	15	131	06	25	3	Alpha	ALH	23	42	146	42	48
3	Argyle Downs	ARD	16	17	128	47	24	4	Atterton	ATT	17	17	145	31	50
5	Aurukun	ARK	13	21	141	44	55	5	Ayr	AYR	19	36	147	25	65
7	Banchory	BNC	23	00	147	06	24	6	Beagle Bay	BGB	16	53	122	40	30
9	Binbee	BNB	20	13	147	54	31	10	Berris Plains	BHL	16	07	136	09	34
11	Bowen	BWN	19	54	145	16	54	12	Brome	BRM	17	57	122	15	31
13	Bullialla	BLW	21	36	146	37	58	14	Burketown	BKT	17	46	139	34	65
15	Cape York	CYK	10	43	142	28	43	16	Caroon	CRG	20	00	144	54	34
17	Carlton Hill	CRH	15	30	128	32	50	18	Charters Towers	CHT	20	05	146	17	63
19	Chillagoe	CLG	17	06	144	50	50	20	Clarke River	CLR	13	12	145	30	31
21	Clermont	CLM	22	48	147	36	47	22	Cloncurry	CLC	20	40	140	30	78
23	Coen	CON	13	54	143	10	45	24	Dallmanville	DLV	20	33	147	57	36
25	Cooktown	CKT	15	28	145	15	55	26	Drysdale	DRD	18	12	142	15	34
27	Dalbey	DLB	27	12	151	15	79	28	Daly River	DRM	13	42	130	36	12
29	Darwin	DRW	12	24	130	48	46	30	Derby	DRY	17	18	123	38	30
31	Dotswood	DTW	19	36	146	18	31	32	Drysdale River	DDR	15	00	126	52	26
33	Dunbar	DNB	16	01	142	24	33	34	Fairview	FRV	15	33	144	19	41
35	Georgetown	GRC	16	22	143	32	58	36	Gladstone	GLS	23	50	151	17	63
37	Gibb River	GBR	16	25	126	22	36	38	Gilbert River	GLR	18	12	142	54	42
39	Giru	GIR	19	31	147	06	37	40	Green Vale	GRV	19	00	145	07	42
41	Gumlu	GML	19	54	147	42	23	42	Hugenden	HGD	20	51	144	13	58
43	Ingham	IGM	18	42	146	12	48	44	Kangaroo Hills	KGH	18	54	145	42	60
45	Katherine	KTR	14	28	132	18	71	46	Kunmunya	KMY	15	25	124	43	26
47	Laura	LUR	15	36	144	27	63	48	Lockhart R.M.	LKR	12	59	143	30	23
49	Lyndhurst	LDH	19	00	144	30	60	50	Mapoon	MPN	12	04	141	55	30
51	Marlborough	MRB	22	48	149	54	61	52	Mary Vale	MRY	19	30	145	18	35
53	Mingela	MNG	19	54	146	36	63	54	Mirina	MRT	21	18	146	12	60
55	Mitchell River	MFR	15	31	141	36	56	56	Mitchell	MTC	26	29	147	58	73
57	Moreton	MRS	12	27	142	32	37	58	Mt. Garnet	MGN	17	41	145	07	34
59	Mt. House	MTH	17	06	125	42	32	60	Mt. McConnell	MML	20	48	147	00	62
61	Mt. Surprise	MSP	17	51	143	42	63	62	Musgrave	MSG	12	01	141	47	34
63	Newry	NWR	16	00	129	16	34	64	Normanton	NRT	17	40	141	05	64
65	Oenpelli	ONP	12	20	133	04	38	66	Palmerville	PLV	16	42	143	54	55
67	Pentland	PNL	20	30	145	24	30	68	Pine Creek	PNC	13	50	131	50	36
69	Ravenswood	RVW	20	06	146	54	64	70	Richmond	RCM	20	44	143	08	66
71	Strathmore	STM	17	53	142	31	39	72	Timber Creek	TBC	15	39	130	30	31
73	Thursday Is	TDI	10	36	142	12	33	74	Townsville	TWV	19	17	146	48	65
75	Van Rook	VRK	16	59	141	54	30	76	Victoria R.D.	VRD	16	24	131	00	35
77	Walsh River	WSR	16	42	143	54	42	78	Wando Vale	WDV	19	42	144	54	30
79	Weipa	WIP	12	41	141	54	25	80	Willeroo	WLR	15	18	131	30	31
81	Woodstock	WDS	19	36	146	48	60	82	Woodhouse	WDH	19	55	147	07	36

## APPENDIX E

### COMPUTATIONAL DETAILS OF POTENTIAL EVAPOTRANSPIRATION [PE]

Potential evapotranspiration is defined as the amount of moisture lost through transpiration by a short green sward fully covering the ground surface with an unlimited water supply (Penman, 1948). It is basically a parameter estimated from meteorological data. There are two important problems associated with the estimation of PE:

- the identification of suitable method(s) for the estimation of PE;
- the availability of input data for the identified model.

The literature is replete with methods for the estimation of PE. These methods can be arranged into two categories, namely empirical and semi-empirical methods. Empirical methods define the simple regressions that relate PE with other meteorological parameters, selected arbitrarily. The major limitation of these techniques is that the constants derived from regression analysis are location-specific. The empirical methods have limited application in global studies. A detailed listing of such methods is given by Reddy (1979c). The semi-empirical methods are derived by taking into account the physical processes involved and the constants are obtained by the regression technique using the observed data sets over time and space and hence these are termed semi-empirical methods (in the literature they are grouped under physical models as their fundamental structure is based on physical concepts). They are the aerodynamic, (the mass-transfer or eddy flux or correlation), the energy budget and the combination of aerodynamic and energy balance. These techniques can be extended to other regions. However, they also have limitations, because, the parameters used may not represent the entire physical process and sometimes regional or local effects dominate and modify the physical processes (Reddy & Amorim, 1984; Reddy et al., 1984b), e.g., advection, which is a major contributing factor to PE under dry conditions.

Among these the most widely used method is the Penman (1948) combination approach. Some of the details of this model along with some of the modifications suggested by scientists are briefly presented below:

**Penman's PE model and its forms:** Penman (1948) gave the first physically sound treatment of the difficult problem of evaporation from a natural surface. The equation which he developed links evaporation rate to the net flux of radiant energy at the surface and to the effective ventilation of the surface by air in motion over it; which means the combination of energy balance and aerodynamic terms into a single relationship. This approach is partly aesthetic and it promotes an understanding of the physical process of evaporation from natural surfaces: it requires meteorological information at one level only, i.e., at 4' above ground level. However, in the form of Penman's equation in current widespread use (see e.g., Grindley, 1970) there is a certain incompatibility between the aerodynamic and energy balance terms (Thom & Oliver, 1977). This has led many workers to suggest ways in which the Penman equation might be modified. The rate of evaporation from an open water surface (Penman, 1948) can be expressed as:

$$E = [\Delta/(\Delta+r)]Q_h + [r/(\Delta+r)]E_a \quad \dots (1)$$

where  $Q_h$  = heat budget, in mm/day

$E_a$  = aerodynamic term, in mm/day

$\Delta$  &  $r$  = efficiency factors which govern the relative effects of energy supply and ventilation

The heat budget term  $Q_h$  is given as:

$$Q_h = R_n/L \quad \dots (2)$$

where  $R_n$  = net radiation,  $\text{cal/cm}^2/\text{day}$

$$\begin{aligned} L &= \text{latent heat of vaporization of water,} \\ &\quad \text{cal/gm} \\ &= 60.74 - 0.00314 T_w \quad \dots (3) \\ &\quad (\text{Blackie \& group, pers. comm.}) \end{aligned}$$

in which  $T_w$  is the wet bulb temperature, in  $^{\circ}\text{F}$ .

The net radiation is given by the equation:

$$R_n = (1-\alpha)R_t - R_l \quad \dots (4)$$

where  $\alpha$  is the albedo or reflectivity of the surface (0.06 for free water surface and 0.25 for vegetation-Monteith, 1959).  $R_t$  is the global solar

radiation in  $\text{cal/cm}^2/\text{day}$ ;  $(1-\alpha)R_t$  represents the net short wave radiation received by a surface and  $R_l$  is the net outgoing longwave radiation or back radiation,  $\text{cal/cm}^2/\text{day}$ . The back radiation may be estimated using the following equation:

$$R_l = \sigma T_k^4 [0.56 - 0.092 e_d^{1/2}] \times [0.1 + 0.9(n/N)] \quad \dots (5)$$

where  $\sigma$  is the Stefan-Boltzmann constant  $[= 1.1707 \times 10^{-7} \text{ ly/day/K}^4]$ ;  $T_k$  is the mean absolute air temperature;  $e_d$  is the vapour pressure of the air in mm Hg;  $n$  is the actual sunshine hours and  $N$  is the theoretical maximum possible sunshine hours.

These parameters therefore suggest that the energy balance term is very dependent upon the accuracy of measurement of net radiation. This in turn, often depends upon the accuracy of total solar radiation estimates.

The coefficients in the Brunt equation (eq. 5) presented by Penman (1948) are not generally applicable to arid conditions. Use of the Penman constants in the Brunt equation for arid conditions overestimates the net outgoing radiation under low humidities (Fitzpatrick & Stern, 1965). Jensen et al. (1971) used the following equation for the estimation of  $R_l$ :

$$R_l = [a(R_t/R_A) + bR_{l0}] \quad \dots (6)$$

where  $R_{l0}$  is the net outgoing longwave radiation in  $\text{cal/cm}^2/\text{day}$  on a clear day and  $R_A$  is the solar radiation that would normally be expected on clear days which can be obtained from estimates of Fitz (1948).  $R_{l0}$  is given as follows:

$$R_{l0} = [0.98 - (0.66 + 0.044 e_d^{1/2})] \times [T_{\max}^4 + T_{\min}^4]/2 \quad \dots (7)$$

in which  $T_{\max}$  and  $T_{\min}$  represent maximum and minimum daily air temperatures, in degrees absolute ( $^{\circ}\text{K}$ ),  $e_d$  is the saturation vapour pressure at mean dew point temperature, in mb.

Originally the constants  $a$  &  $b$  in equation (6) (1.35 and -0.35) were derived using the data from Davis, California (Pruit, pers. comm.). More recent evaluations (Idaho, pers. comm.) indicate that under arid conditions where nights are frequently clear, the values should be 1.2 and -0.2 for  $a$  and  $b$ , respectively. The constants for the Brunt portion of

equation (7) are similar to those of Goss & Brooks (1956), who obtained values of 0.66 and 0.040 in California, and Fitzpatrick & Stern (1965), who obtained constants of 0.65 and 0.049 in Australia. These coefficients also vary under different climatic regimes, and regional coefficients should be used if available.

The estimation of the incoming radiation term as suggested by Penman is that of Angstrom (1924) which is given as:

$$T_t = R_A [a + b (n/N)] \quad \dots (8)$$

where  $a$  and  $b$  are constants. This equation has been modified by Glover & McCulloch (1958) to:

$$R_t = R_A [0.29 \cos \theta + 0.52(n/N)] \quad \dots (9)$$

However, the radiation measurements at some stations in India, gave values for ' $a$ ' ranging from 0.27 to 0.38 and for ' $b$ ' from 0.33 to 0.44 (Rao et al., 1971). Values of ' $a$ ' and ' $b$ ' obtained by Rao et al. (1971) are slightly lower than those given by Glover & McCulloch (1958). Black et al. (1954) analysed the monthly values of radiation and duration of sunshine of 32 stations from the tropics to the polar regions and found ' $a$ ' equal to 0.32 and ' $b$ ' equal to 0.48. They have also noted that the ' $b$ ' is more or less constant, whereas the value of ' $a$ ' shows marked variation. Glover & McCulloch (1958) explained that the constant ' $a$ ' is dependent upon the optical air mass and hence, the latitude of an area. Using data from seven stations covering the range of  $0^\circ$  to  $60^\circ$  latitude, they found the constants presented in eq. (9). The latitude correction applied by them is questionable as  $R_A$  itself depends upon the latitude and season. It can be seen from the study of Reddy (1971a) that the estimates of  $R_t$  are also significantly influenced by relative humidity of the atmosphere. Hounam (1958) states that "the Angstrom type of equation can be expected to give only an approximate value of solar radiation because the regional variation of atmospheric turbidity is not considered". He says that there might be a large difference in atmospheric water content on clear and cloudy days at Townsville, but not at Melbourne, therefore, the ratio  $R_t/R_A$  would be lower at Townsville. The accuracy of the estimates of Penman's method therefore depends upon the accuracy with which the net radiation term is estimated as it has a greater influence than the aerodynamic term.

The aerodynamic term  $E_a$ , in mm water equivalent for PE is given as:

$$E_a = 0.35 (1+U/100) (e_a - e_d) \quad \dots (10a)$$

In which the estimation of evaporation from a free water surface (E):

$$E_a = 0.35(0.5+U/100)(e_a - e_d) \quad \dots (10b)$$

where  $U$  is the wind speed in miles/day at 2 metre level,  $e_a$  is the saturation vapor pressure in mm Hg and  $e_d$  is the actual vapor pressure in mm Hg.

Rao et al. (1971) pointed out that in the original derivation of the equation, 'r', is taken to depend on mean air temperature only; recent studies have shown that this factor depends on altitude. A correction is therefore applied by multiplying  $\Delta/r$  by  $P_0/P_h$  similar to Van Bavel (1966) where  $P_0$  is the standard sea level pressure (1013.2 mb) and  $P_h$  normal station level pressure of 0830 hours IST observation. This gives a proportionate increase for the energy term over the aerodynamic term and a reduction of the overall numerator energy term. McCulloch (1965) suggested in a different way, as  $E_a[1+h/2000]$ , where  $h$  is the altitude in metres. Consequently, there is a proportionate increase in the aerodynamic term, which is just the opposite effect to that of Rao et al. (1971).

The psychrometric constant represents a balance between sensible heat gained from air blowing past a wet bulb thermometer and sensible heat transformed into latent heat. This constant is directly dependent upon air pressure or more specifically altitude, and to a much smaller extent upon air temperature.

$$\Delta = e_a [ (6790.498/T) - 5.02808 ], \text{ mm/}^{\circ}\text{C}$$

$$r = [1013 - 0.1h] \times 0.0002727, \text{ where } h \text{ is altitude in metres}$$

$$e_a = \text{Exp} [54.878919 - (6790.4985/T) - 5.02808 \log_e T]$$

The mean wind speed  $U_h$  in km/hr reported at the anemometer level ( $h$  metres) can be converted into wind speed in miles/day at 2 meters level by using the relation:

$$U = U_h [2/h]^{0.17} \times (5/8) \times 24 \text{ miles/day}$$

Following several tentative generalizations Frere (1978) presented a manual for rapid computation of PE or E from Penman's (1948) equation. However, it was found (Reddy & Amorim, 1984) that its application is quite limited in some cases, unless a good regional parameters are available. PE is obtained for different countries using the following procedures and the data are standardized with open pan evaporation:

1. Wherever observed pan evaporation (E) data are available over a good network of stations in a country, then PE is obtained for each location wherever the rainfall data are available as follows: plot the E values in terms of geo-coordinates and draw isolines. While drawing isolines give proper weight to local factors (which are estimated through regression). This procedure is carried out for each month. From this monthly data set PE is obtained as:  $PE = 0.85E$ . This relationship was obtained by comparing PE and E estimates using Penman's method over 30 locations in India distributed widely both in latitude and longitude (Reddy & Reddy 1973). This was found by Reddy & Amorim (1984) to be valid for other parts of the world. This procedure is adopted in the case of Brazil, Australia (H.A. Nix, pers. comm.) and Thailand.
2. In the case of Africa a different procedure is adopted, as both pan evaporation and other meteorological data needed as inputs to other models are rarely available. The PE data for about 30 locations were presented by Cocheme & Franquin (1967). These were estimated using the modified Penman approach of Frere (1978). These estimates are comparable with PE values derived from E. Therefore, using this data set a regression model (Reddy & Virmani, 1980a) was developed with reference to latitude and longitude. Through this regression model PE values were estimated on a  $1^\circ$  grid network and interpolated graphically. While drawing the isolines for the estimation of PE, the procedure mentioned in the first para(above) is adopted. PE data for 300 locations for west Africa are obtained by this procedure and for other regions in Africa, the PE data presented by FAO (M. Frere, pers.comm.) are used [estimated using the modified Penman's approach].
3. In India, Rao et al. (1971) presented PE values for about 300 locations. These were estimated using the modified (according to them) Penman's approach. The PE values are adjusted by pan evaporation data at about 30 locations.

However, all these data sets represent average monthly values only. The monthly PE values are therefore graphically interpolated and weekly average values are obtained. From these average weekly data sets the individual yearly weekly values are derived following the procedure of Reddy (1979a) as follows:

$$PE_n = PE'_n [1.0 + 0.06 |Z_n|^{1/3}] \quad \dots (11)$$

where

$$Z_n = [\Delta R_n + (1/3)\Delta R_{n-1}]$$

$PE_n$  = estimated PE in year Y on the nth week, mm/day

$PE'_n$  = average weekly PE on the nth week, mm/day

$$\Delta R_n = R_n - R'_n$$

$R_n$  = weekly rainfall in year Y on the nth week, mm/week

$R'_n$  = average weekly rainfall on the nth week, mm/week

+ 0.06 if  $Z_n$  is negative or -0.06 if  $Z_n$  is positive

$|Z_n|$  is the absolute value of  $Z_n$



## APPENDIX F

### NUMERICAL TAXONOMIC PROCEDURES – A REVIEW

Classification procedures vary from conventional descriptive methods to modern computer-based numerical techniques. There are three mutually independent numerical taxonomic techniques, namely ordination, cluster analysis and the minimum spanning tree; and under each there can be several forms of grouping strategies (Fig. 6-1). Therefore, in this appendix, an attempt is made to catalogue and discuss these different methods of classification as they apply to climate and to identify the similarity metric that integrates the attributes of numerical, continuous, data sets.

#### TERMINOLOGY

Before reviewing the similarity metric and classification procedures as shown in Fig. 6-1, it is necessary to address some of the confusing terminology that exists in the literature.

According to Simpson (1961) systematic is the scientific study of the kinds and diversity of objects and of any and all relationships among them; taxonomy is the theoretical study of classification, including its bases, principles, procedures and rules; and classification is the ordering of objects into groups (or sets) on the basis of their relationships, that is, of their associations by contiguity, similarity, or both. Therefore, taxonomy is a part of systematics and classification is a part of taxonomy. Systematics covers wide aspects while the term classification is used in a restricted sense. Here the objects refer to climatic stations.

Individuals or locations or entities (Sneath uses OTU an operational taxonomic units) are the elements to be ordered or classified. Each individual has a number of items of information called attributes/variables (Clifford & Stephenson, 1975 & Williams, 1976). Some workers arrange these into categories, namely quantitative (continuous) and qualitative, for the sake of simplicity. The quantitative attributes are often known as metric attributes.

The terms similarity measure or similarity coefficient or similarity metric are synonymous. They involve the integration of different attributes through a mathematical function to provide a similarity or dissimilarity parametre. With the correlation coefficient the highest value indicates close similarity while in the case of distance measures, the lowest distance represents the most similar, because it is inappropriate to compare differences in attributes having a range of 0.0 to 1.0 with those with a range of 100 to 1000. The importance of bringing all these to a single range of 0 to 1 by a suitable method is emphasized. This process is known as standardization.

Exclusive refers to a given element occurring in one class and one class only. Non-exclusive refers to a given element that may appear simultaneously in more than one sub-class. Under intrinsic all attributes are regarded as equivalent while in the extrinsic an external attribute is declared in advance, i.e., specification is given in advance about an attribute. Agglomerative refers to a type of clustering algorithm which operates by successive grouping together of objects. Under monothetic, a class is defined by a single attribute while in the polythetic a class is defined by more than one attribute. Monothetic classifications are those in which the classes established differ by at least one property while in polythetic classifications groups of individuals share a large proportion of their properties, but do not necessarily agree in any one property. Hierarchical refers to the process of optimization of a route between the entire population and the set of individuals of which it is composed, while under non-hierarchical systems, the structure of the individual groups are optimized. Clustering is the formation of groups defined by hierarchical or non-hierarchical methods. A method of cluster analysis is said to be stable if small changes in the data lead to commensurately small changes in the results. A dendrogram is the diagrammatic illustration of relationships based on the degree of similarity. A nested-hierarchy permits grouping of a large number of taxonomic groups into fewer groups of higher rank. It is only when these groupings are mutually exclusive that optimum results can be achieved (for example, a given class at a level A can belong to only one class A' at level X-1, and this class A' to only one class A" at level X-2, and so on). Ordination refers to the disposition of individuals in a reduced space defined by fewer axes than the original number of properties studied for those individuals.

If the distance from other objects contracts as the number of individuals in a group increases, this is known as a space-contracting clustering strategy. Space-dilating strategies produce the opposite effects: as groups grow in size, they appear to recede from all other objects, and the chance of more individuals joining that group diminishes. Space-conservation refers to a situation where contraction and dilation effects are not evident.

Eigenvalue refers to the latent root of the data matrix (a scalar) and eigenvector refers to the latent vector of the data matrix (a vector). Some of the terms like R- and Q- techniques; A- and I- space can be simplified by using rows as characters, the pairs for which association is to be examined, and columns by the attributes.

## DATA MATRIX

The first and major task in classification is to identify available data sets. There are two problems associated with data collection, namely availability and accuracy. There are several forms of attribute namely binary, numerical etc., but the present discussion is restricted to numerical continuous data sets only. Some details on the types of attributes are presented in Chapter 3. Table F-1 presents a sample of the data matrix representing 11 Indian locations, each with 11 agroclimatic attributes. At the bottom of this matrix is also presented the mean, standard deviation (hereafter referred as s.d.) and range of each attribute over these locations. In this  $G'$ ,  $W'$ , and  $D'$  are derived through a functional relationship while  $s$ ,  $G$ ,  $C$ ,  $W$ ,  $\alpha$ ,  $D$ ,  $\beta$  and  $A$  are derived attributes. One can qualitatively distinguish two groups in Table F-1, namely (i) locations 1 to 4 and (ii) locations 5 to 11. In group (i), location 1 is closer to 3; while 2 and 4 show anomalies with respect to certain attributes. In group (ii) 6 is closer to 7; and 5 is closer to 6-7 and 9 is closer to 5-7. 10 is equidistant from 8 and 11. It appears, however, that 10 is closer to 8 compared to 11 in the majority of the attributes.

## SIMILARITY MEASURES

For better representation of a location, it may be important to use more items of information (attributes). The complexity of dealing with more than two attributes can be simplified by attribute integration using standard mathematical functions. Ideally, these produce summary coefficients representative of locational differences. The literature is abundant with

Table F-1 : Data matrix representing 11 locations with 11 attributes.

S.No.	Location	Attributes*										
		$\delta$	$\bar{G}$	C	$\bar{W}$	$\alpha$	$\bar{D}$	$\beta$	G'	W'	D'	A
1	Indore	1.3	16.4	19	7.0	2.2	6.0	2.1	2.8	2.3	1.3	00
2	Ranchi	2.9	16.4	23	7.5	3.4	3.7	1.8	0.7	2.8	-1.0	00
3	Mahboobnagar	2.5	16.6	30	5.8	2.7	6.0	2.6	-2.1	1.1	1.3	05
4	Vishakhapatnam	4.4	16.7	50	5.3	3.3	7.1	4.2	-6.4	0.6	2.4	14
5	Hyderabad	2.9	12.9	45	4.2	2.5	5.0	2.5	-1.8	-0.5	0.3	13
6	Sholapur	4.0	11.3	57	3.6	2.0	5.1	3.0	-1.8	-1.1	0.4	24
7	Ongole	5.6	11.2	58	3.7	2.2	6.0	3.2	-1.8	-1.0	1.3	24
8	Ajmer	1.5	7.6	67	3.6	1.8	3.7	2.1	0.9	-1.1	-1.1	30
9	Chittoor	5.0	8.9	92	3.6	3.1	4.3	3.7	-2.0	-1.1	-0.4	44
10	Anantapur	4.8	5.2	104	2.7	1.7	3.7	2.5	1.2	-2.0	-1.0	52
11	Hissar	5.9	2.0	170	2.1	1.4	3.0	1.4	2.8	-2.6	-1.7	74
Mean		3.7	11.4	65	4.5	2.4	4.9	2.6	-0.7	-0.2	0.2	25
S.D		1.5	3.3	42	1.6	0.6	1.2	0.8	2.5	1.6	1.2	19.5
Range		4.6	14.6	151	5.4	2.0	4.1	2.8	9.2	5.4	4.1	74

\*  $\delta$  = Standard deviation of Commencement of sowing rains, weeks

$\bar{G}$  = Mean effective rainy period, weeks

C = Coefficient of variation of G, %

$\bar{W}$  &  $\bar{D}$  = Mean number of wet and dry spells within G, weeks

$\alpha$  &  $\beta$  = Standard deviation of wet and dry spells, weeks

G' =  $G'' - \bar{G}$ , G'' is derived through a functional relation ( $\bar{G}$  vs C), weeks

W' =  $\bar{W} - W''$ , W'' is derived through a functional relation ( $\bar{G}$  vs  $\bar{W}$ ), weeks

D' =  $\bar{D} - D''$ , D'' is derived through a functional relation ( $\bar{G}$  vs  $\bar{D}$ ), weeks

A = Percentage crop failure years or riskyness in crop production, %

such measures. Sneath & Sokal (1973) grouped these under four types, namely probability coefficients; association coefficients (also known as coefficient of similarity or matching coefficients); correlation coefficients and distance coefficients (or measure of distance or dissimilarity measure). The first two are not used with continuous (numerical) data but are commonly used with binary or qualitative data. Association and correlation coefficients can usually be related to distances. Distance coefficients and the correlation coefficients along with geometric representation are presented below.

### Distance coefficients

Distance coefficients are of two types: non-standardized (e.g., Euclidean metric, Mean character distance (MDC)) and standardized (e.g., Canberra metric, Gower metric).

#### Non-standardized distances:

Several distance coefficients have been proposed as measures of inter-individual relationships (Sneath & Sokal, 1973). Coefficients chosen to represent the relationship between individuals are calculated for all pairs of individuals from the original data matrix. The choice of coefficient requires a knowledge of their relative merits and the kinds of taxonomic information produced. A geometric model is helpful in understanding the meaning of similarity coefficients. Individuals to be studied are thought of as points lying in a multidimensional space, the axes of which correspond to attributes. Let  $X_{hk}$  represent the data matrix with  $k$  attributes for  $h$  locations. Figure F-1 presents a geometrical representation of locations A and B in space defined by two axes. For simplicity it is assumed that each attribute is an orthogonal coordinate amenable to simple Pythagorean geometry. From the trigonometric relationship with ABC representing a right angled triangle, the distance between two locations (AB) is given as:

$$\begin{aligned} AB = \Delta &= [BC^2 + CA^2]^{1/2} \\ &= [(x_{21} - x_{11})^2 + (x_{12} - x_{22})^2]^{1/2} \\ &= [\sum_{k=1}^p (x_{ik} - x_{jk})^2]^{1/2} \end{aligned}$$

The taxonomic distance  $d_{ij}$  is related to the geometric distance by:

$$d_{ij} = [\Delta_{ij}^2 / p]^{1/2}$$

This is also known as Euclidean or Pythagorean distance (Table F-2, eq. 1)

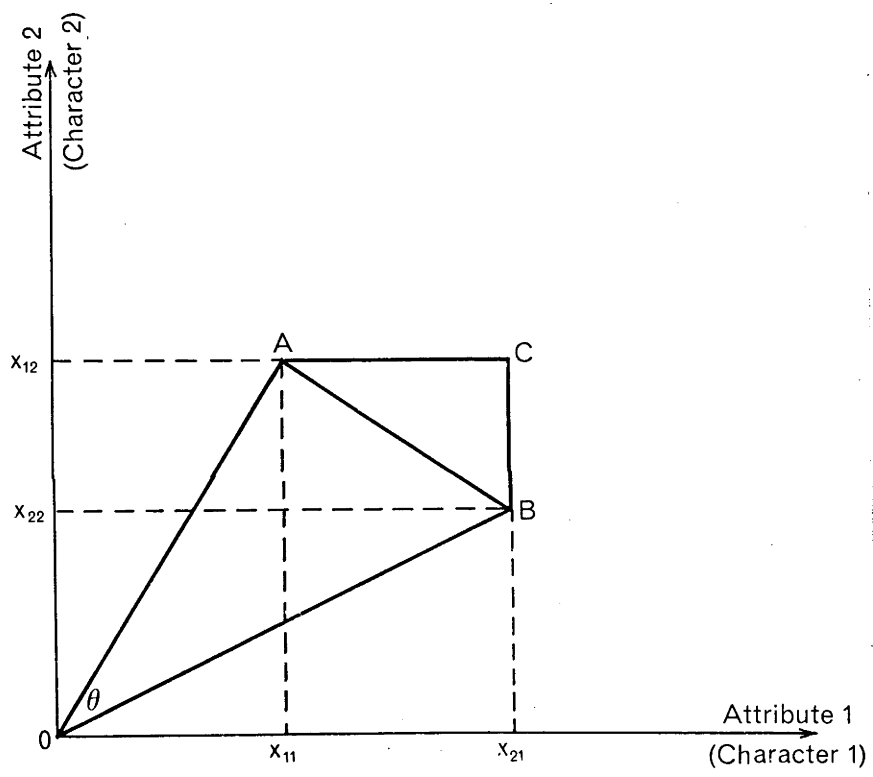


Figure F-1 : Geometric presentation of similarity measures.

-- refer to Table F-2 only, hereafter). This represents the square root of the average of the squared differences between individuals over all attributes ( $p$ ).  $d_{ij}$  measures the dissimilarity between the individuals  $i$  and  $j$ . Such a measure is sensitive to the magnitude of the difference between the attributes: larger differences will contribute a relatively greater amount to the sum of squares of the differences. To prevent excessive dominance by attributes with large differences, prior data standardization is usually required. The MCD is also known as the Manhattan or City block metric (Cain & Harrison, 1958) representing the absolute average difference between individuals (eq. 2). The above two metric could be standardized either by dividing each difference by the standard deviation of the locations  $(s.d.)_k$  -- eqs. 6 & 9 -- or by the range  $r_k$  of the respective attributes ( $k$ ) -- eqs. 8 & 10. The standardized dissimilarity metric can be expressed as similarity metric by  $S_{ij} = 1 - d_{ij}$ . Squared standardized Euclidean distance is also known as Mahalanobis generalized distance. If the standardization is made using the standard deviation then the squared Euclidean distance is also known as Burr standardized squared Euclidean distance (eq. 7).

In the above two methods, the squared or absolute difference specifies the importance of magnitude rather than the sign of the difference. However, the resultant magnitudes in both cases, differs substantially because it represents a second order difference in the former, and first order difference in the latter.

#### Standardized distances:

The Canberra metric (Lance & Williams, 1967b) is defined as the average of the ratio of absolute difference by the total of the two entities. Its use is restricted to positive values only unless a correction to the denominator is made. Such a procedure was suggested by Gower (Sneath & Sokal, 1973) is applied as  $(|x_{ik}| + |x_{jk}|)$ . By using  $|x_{ik}|$  instead of  $x_{ik}$  the resulting distances change completely and thereby the whole final system. For example: if four locations had attributes - 4, 8, 12, 16, the corresponding distances in the above two cases are: 3, 2, 5/3 and 1, 1, 1. In the former they are highly dissimilar while in the latter they are highly similar.

Bray & Curtis (1957) suggested a slightly different similarity metric (eq. 4). The difference between the Canberra metric and the Bray-Curtis measure is that, in the former, the distance represents the sum of

Table F-2 : Different forms of distance measures .

Measure of distance	$d_{ij}$	Eq. No.
(a) <u>Non-standardized metric:</u>		
Euclidean metric	$((\sum_{k=1}^p x^2)/p)^{\frac{1}{2}} = E$	1
MCD	$(\sum_{k=1}^p  x )/p = M$	2
(b) <u>Standardized metric:</u>		
Canberra metric	$(\sum_{k=1}^p ( x /(x_{ik}+x_{jk}))/p$	3
Bray-Curtis metric	$(\sum_{k=1}^p  x )/(\sum_{k=1}^p (x_{ik}+x_{jk}))$	4
Gower <sup>*</sup> metric	$(\sum_{k=1}^p (1 - \frac{ x }{r_k}))/p$	5
Standardized Euclidean metric	$E/s.d._k$	6
Burr Standardized Euclidean metric	$(E/s.d._k)^2$	7
Euclidean metric with range	$E/r_k$	8
MCD with s.d.	$M/s.d._k$	9
MCD with range	$M/r_k$	10

\* Represents the similarity coefficient:  $S_{ij} = 1-d_{ij}$

$r_k$  = Range of attribute k;  $s.d._k$  = Standard deviation of attribute k;

$x = x_{ik} - x_{jk}$



average absolute differences of attributes divided by the sum totals. In eq. 3 both numerator and denominator carry a summation symbol; the ratio tends to be greatly influenced by occasional outstanding values. By contrast in the Bray-Curtis measure (eq. 4) the outstanding differences can only contribute to one of the fractions and so does not come to dominate the index (Clifford & Stephenson, 1975). It will be noted that both the Bray-Curtis and the Canberra measures of dissimilarity involve, at each stage, only one pair of entities under consideration.

The general similarity coefficient of Gower (1971) is similar to the MCD but is divided by the range, taking into account both positive and negative values (eq. 5). There is also a provision to give weights or masking to different attributes. The MCD represents the dissimilarity measure ( $d_{ij}$ ) while the Gower metric represents the similarity measure ( $S_{ij}$ ). At each stage the Gower metric considers the entire population in terms of the range ( $r_k$ ) of a particular attribute  $k$ .

The basic differences among these distance measures stem from three factors:

1. use of the absolute difference or the squared difference between pairs in the numerator;
2. use of the population range or s.d. of an attribute or pair sum of attributes in the denominator with a summation on the numerator;
3. use of the single summation for both numerator and denominator with pair sums of individual attributes in the denominator.

The latter two contribute to the major differences in similarity matrices. The similarity matrix obtained with population range or s.d. in the denominator does not change the original order obtained by the numerator. Therefore, it works as a true standardization procedure, retaining the original order shown by the data matrix. In other situations, the original order is changed substantially, hence some similarity estimates gain undue weight, and this is a disadvantage.

#### Correlation coefficient

The Pearson product-moment correlation coefficient ranges between -1 and +1. Boyce (1969) presented the correlation coefficient in terms of the angular measure as (Fig. F-1):

$$d_{ij}^2 = 2(1 - \cos\theta)$$

If  $\theta$  is zero, then the two locations A and B lie on the same straight line passing through the origin 'O'. This means  $x_{ik} = a x_{jk}$  for all values of  $k$  where  $x_{ik}$  and  $x_{jk}$  represent the values of the  $k^{\text{th}}$  attribute for locations  $i$  and  $j$ . 'a' is known as the proportional constant while, in this case, the correlation coefficient is unity (+ve if both A and B lie on the same side of the origin and -ve if they lie on opposite sides of the origin). This suggests that angular measures or correlation coefficients are not correct measures to represent true distance between any two locations in terms of their attributes. The product-moment correlation coefficient c.c., therefore, ignores the proportional differences being equal to the cosine of the angle between two locations when the attributes of the respective locations are expressed as deviates from the mean of all attributes. The new data matrix of the individual stations is represented by zero mean and unit variance. Therefore, the c.c. is non-metric. When converted to some simple complementary form, corresponding to distances, it does not obey the triangle inequality and it can also be shown that perfect correlation could occur between non identical individuals. These properties of the correlation coefficient limit its applicability and it is therefore regarded as inappropriate (Webster, 1979).

More appropriate and mathematically sound similarity measures for numerical (continuous) data appear to be the standardized Euclidean metric and the Gower metric.

### **Standardization and transformation**

Smith (1976) suggested several standardization procedures. The s.d. in the case of second order deviations (Euclidean metric), the equivalent of variance  $[(s.d._k)^2]$  in the case of a squared Euclidean metric, and range in the case of first order metric such as the Gower metric represent mathematically appropriate standardization procedures. Using the data matrix of Table F-1, the similarity measures were computed using eqs. 1 & 2 and standardization both by the range and s.d. (eqs 6, 8-10). These results suggest that the magnitude of similarity measures (Table F-3) obtained by using range standardization are lower than those obtained using s.d. When dispersion is greater among the attributes of two locations, the ratios are slightly higher compared with the contrary situation. Sometimes these small variations of individuals may be sufficient

Table F-3 : Similarity matrices for different similarity measures with different standardization procedures using the data presented in Table F-1.

	Locations										
	1	2	3	4	5	6	7	8	9	10	11
I. $\underline{M/K^*}$											
1	0.00	0.33	0.22	0.50	0.31	0.41	0.46	0.44	0.56	0.60	0.79
2	0.24	0.00	0.32	0.55	0.38	0.46	0.51	0.47	0.49	0.60	0.77
3	0.16	0.27	0.00	0.30	0.19	0.29	0.32	0.42	0.41	0.54	0.76
4	0.42	0.45	0.24	0.00	0.38	0.39	0.33	0.62	0.42	0.62	0.86
5	0.28	0.33	0.16	0.29	0.00	0.14	0.23	0.26	0.29	0.36	0.58
6	0.38	0.42	0.26	0.35	0.12	0.00	0.15	0.27	0.24	0.28	0.51
7	0.36	0.49	0.25	0.30	0.17	0.09	0.00	0.41	0.23	0.35	0.56
8	0.38	0.36	0.39	0.56	0.24	0.22	0.31	0.00	0.49	0.26	0.38
9	0.55	0.44	0.38	0.36	0.24	0.19	0.17	0.28	0.00	0.30	0.50
10	0.55	0.49	0.51	0.60	0.33	0.27	0.33	0.18	0.24	0.00	0.23
11	0.72	0.66	0.74	0.83	0.56	0.49	0.52	0.38	0.45	0.21	0.00
II. $\underline{E/K}$											
1	0.00	0.89	0.57	1.40	1.04	1.32	1.27	1.37	1.83	2.05	2.56
2	1.29	0.00	0.91	1.53	1.09	1.48	1.71	1.34	1.57	1.75	2.30
3	0.79	1.80	0.00	0.86	0.59	0.93	0.79	1.33	1.38	1.48	2.43
4	1.88	1.88	1.04	0.00	1.13	1.23	1.08	1.98	1.45	2.07	2.96
5	1.15	1.23	0.69	1.32	0.00	0.41	0.62	0.89	0.89	1.24	2.03
6	1.44	1.59	1.02	1.39	0.48	0.00	0.30	0.75	0.62	0.96	1.78
7	1.56	1.78	1.02	1.20	0.77	0.47	0.00	1.05	0.74	1.16	1.88
8	1.61	1.67	1.44	2.19	0.97	0.94	1.35	0.00	0.95	0.72	1.33
9	1.90	1.76	1.49	1.60	1.02	0.82	0.91	1.25	0.00	0.84	1.62
10	2.20	2.15	1.74	2.23	1.36	1.05	1.27	0.97	1.05	0.00	0.80
11	2.85	2.69	2.61	3.10	2.15	1.90	2.05	1.56	1.78	0.89	0.00

\* M = MCD from Eq. 2 & E = Euclidean metric from Eq. 1  
 K = s.d.<sub>k</sub> (upper triangle) : here M/K represents Eq. 9  
 : & E/K represents Eq. 6  
 & K = r<sub>k</sub> (lower triangle) : here M/K represents Eq. 10  
 : & E/K represents Eq. 8

Eq. Nos. are as referred in Table F-2.

to alter groups. Results emphasize the fact that the new way of standardization is not superior to conventional procedures: the Euclidean metric by s.d. and the MCD by range (the latter represents the Gower metric) -- eqs. 5 and 6.

Smith (1976) suggested data transformations, one viable standardization procedure. By transformation, undue weight is often given to some attributes, and with square root or exponential transformations, the distortion in the original data is too large and tails off to one end thereby reducing the range of variation. Such a characteristic behaviour is a weakness in any classification technique. This procedure is generally used to derive a relationship between two parameters if they are curvilinearly related by converting curvilinearity to linearity before regression. Ivimey-Cook (1969) states that it is difficult to produce an absolute justification for this course of action in every case, but, on the other hand, there is no special virtue in the conventionally used linear scale of measurement.

## CLASSIFICATION PROCEDURES

Classification procedures can be divided into graphical and numerical. The former represents the traditional approach while the latter represents more modern computer techniques. Each has advantages and disadvantages in their application to climatic classification studies.

### GRAPHICAL PROCEDURES

The general practice is to present the spatial distribution of an attribute(s) in geo-coordinates. Zones are identified by dividing the attributes at discrete intervals. These studies are not only based on observed climatic parameters such as rainfall and temperature but also on derived parameters like potential evapotranspiration. Details on some of the graphical procedures were presented in Chapter 2. In these studies, climate is classified using attributes one at a time. Climatic boundaries are chosen arbitrarily corresponding to certain critical values of vegetation types. However, since the limits are more subjective, clearly reflecting personal bias.

The second graphical procedure is the shading of areas of equal similarity measure. The widely used similarity measures are the correlation coefficient (Rao et al., 1972b) and principal coordinates or components (Dyer, 1975). The aims of such studies are twofold: identification of homoclims that can be used as a predictive measure. This approach, however, is limited to regional studies only.

The first of these two graphical procedures are in wide use at both regional and global scales, the second is in use only in studies at the regional scale. These are traditional descriptive approaches that are limited in the number of attributes, while limits used in the demarcation of boundaries reflect the personal bias of the climatologist. The major advantage of these procedures is that they represent a continuum in geo-coordinates which facilitate interpretation and assist validation of results.

#### NUMERICAL PROCEDURES

Numerical methods have become feasible in recent years with the advent of computers. In general, humans are unable to manipulate any considerable mass of data in an integrated fashion, yet the computer is no more efficient than its program and may only be as efficient as a highly trained taxonomist. Using numerical procedures there are three mutually exclusive techniques: Ordination, Cluster analysis and Minimum spanning tree (MST).

##### Ordination

The two common procedures that are in wide use are principal component analysis and principal coordinate analysis.

##### Principal component analysis (PCA):

In the PCA first rows are standardized (unit variance, zero mean) to give a square matrix of moment correlation coefficients between pairs of rows. Computing the principal components of this matrix involves the computation of its eigenvalues and eigenvectors. The importance of these vectors is that they are orthogonal. In other words, a large proportion of the dispersion engendered by the  $n$  rows over the  $m$  columns may be accounted for by  $p$  dimensions. PCA can also be carried out on a variance-covariance matrix (for details see Craddock & Flood, 1969; Craddock, 1973; and Barnett, 1977).

The  $p$ -normalized vectors give the directions of a set of  $p$  orthogonal axes in  $p$ -dimensional space and are known as the principal axes. The linearly independent principal components are ranked in terms of the amount of the total variance each component explains. The first component explains the largest proportion of the data variance. The second component is orthogonal to the first and explains the second largest amount of variance and so on. Most of the variance in the original data matrix can be explained by a few new components: often as few as 3 principal axes will suffice.

PCA adheres strictly to the geometry of the original Euclidean model. Situations where principal components can be interpreted in any physical sense are largely fortuitous: principal components are mathematical constructs, and do not necessarily have any physical meaning. There have been numerous attempts to obtain meaningful variates from combinations of others using methods that are known collectively as factor analysis (Catel, 1952). These are simple analytical rotation of principal components.

#### Principal coordinate analysis (PCO):

The PCO technique developed by Gower (1966) is an important advance in ordination techniques. He has shown that with a suitable measure of similarity or dissimilarity between individuals, coordinates can be found relative to principal axes. The first step in the analysis is to calculate a distance  $d_{ij}$  between every pair of rows,  $i$  and  $j$  or, from similarity indices,  $S_{ij}$ , by scaling in the range 0 (for maximum possible dissimilarity) to 1 (for identity) and  $d_{ij} = [2(1-S_{ij})]^2$ . From these distances a matrix  $Q$  can be formed with elements -  $q_{ij} = (1/2) d_{ij}^2$ . The matrix  $Q$  is now adjusted by subtracting from each element the corresponding row mean ( $q_i$ ) and column mean ( $q_h$ ) and adding the grand mean ( $q$ ). Thus, the new matrix  $F$  can be formed with elements:

$$f_{ih} = q_{ih} - q_i - q_h + q$$

The latent roots and vectors of  $F$  are found, and the vectors are arranged as columns in an  $n \times n$  matrix; the rows representing coordinates of the individuals. The vectors are normalized so that the sums of squares of their elements equal their corresponding latent roots. This transforms the matrix  $F$  into a new matrix  $G$ . Gower shows that when this transformation is made, and starting from the matrices  $Q$  and  $F$  defined above, the distance between any two points  $i$  and  $j$ , whose coordinates are the  $i$  and  $j$  rows of  $G$ , equals  $d_{ij}^2$ . The latent vectors scaled in this way represent exactly the distances between individuals and defines their positions relative to principal axes.

When the starting matrix consists of Euclidean distances, PCO gives results identical with those of PCA. This means that both are mathematically similar, but the latter is more flexible in terms of similarity measures. However, Webster (1979) states that although PCO is more versatile than PCA, the latter is preferable; while Sneath & Sokal (1973) identified many advantages of PCO over PCA. However, both the methods

suffer from difficulty in interpretation as coordinates or components do not contain physical meaning. One important feature in these studies is the dimensional reduction. When  $p$  is considerably large the dimensions can be used as new attributes with less noise and may be used to represent the spatial variation in geo-coordinates as in the case of graphical presentation.

As an example, PCO was carried out using the data matrix presented in Table F-1 with the squared standardized Euclidean metric. The results of the first 3 coordinates are depicted in Fig. F-2. Locations in coordinates 1 and 2 have a concave while coordinates 1 and 3 have a convex distribution (Fig. F-2). In Fig. F-2, the arrangement of locations into finite groups is subjective.

PCA was used by Dyer (1975) to forecast rainfall and to minimize rainfall collection networks by identifying homogeneous zones in South Africa; by Willimolt (1977, 1978) to classify California into homogeneous zones; by Gadgil & Joshi (1981) to classify India into homogeneous zones and by Reddy & Virmani (1982) to classify the semi-arid tropics of India and west Africa into homogeneous zones. In these studies climatic attributes differ: Gadgil & Joshi used pentad rainfall (72 attributes for 52 locations); Reddy & Virmani used three different attribute sets, namely (i) monthly rainfall (12 attributes); (ii) average weekly rainfall (52 attributes); and (iii) weekly probability of getting 10 mm/week or more rainfall (52 attributes) for 81 locations (43 India + 38 Niger). Their area of study varied from local (Dyer), to regional (Gadgil & Joshi and Willimolt) and inter-continental (Reddy & Virmani) scale. It is evident from these studies that if the proposed classification is only to sub-divide a small region within a uniform general atmospheric circulation pattern, the proposed classification looks quite satisfactory (Dyer, 1975). In such studies one interest is to differentiate the degree of local differences caused by orography, vegetation etc. Sometimes these differences are visually evident. If the interest is to group a nation or nations which have wide circulation patterns superposed on regional or local dissimilarities, then the proposed classification performance is less adequate, with many anomalies (Gadgil & Joshi, 1981 and Reddy & Virmani, 1982). A problem associated with using both correlation or covariance, is that the mean of each station record does not influence the level of similarity between station records as these coefficients describe deviations about means. As

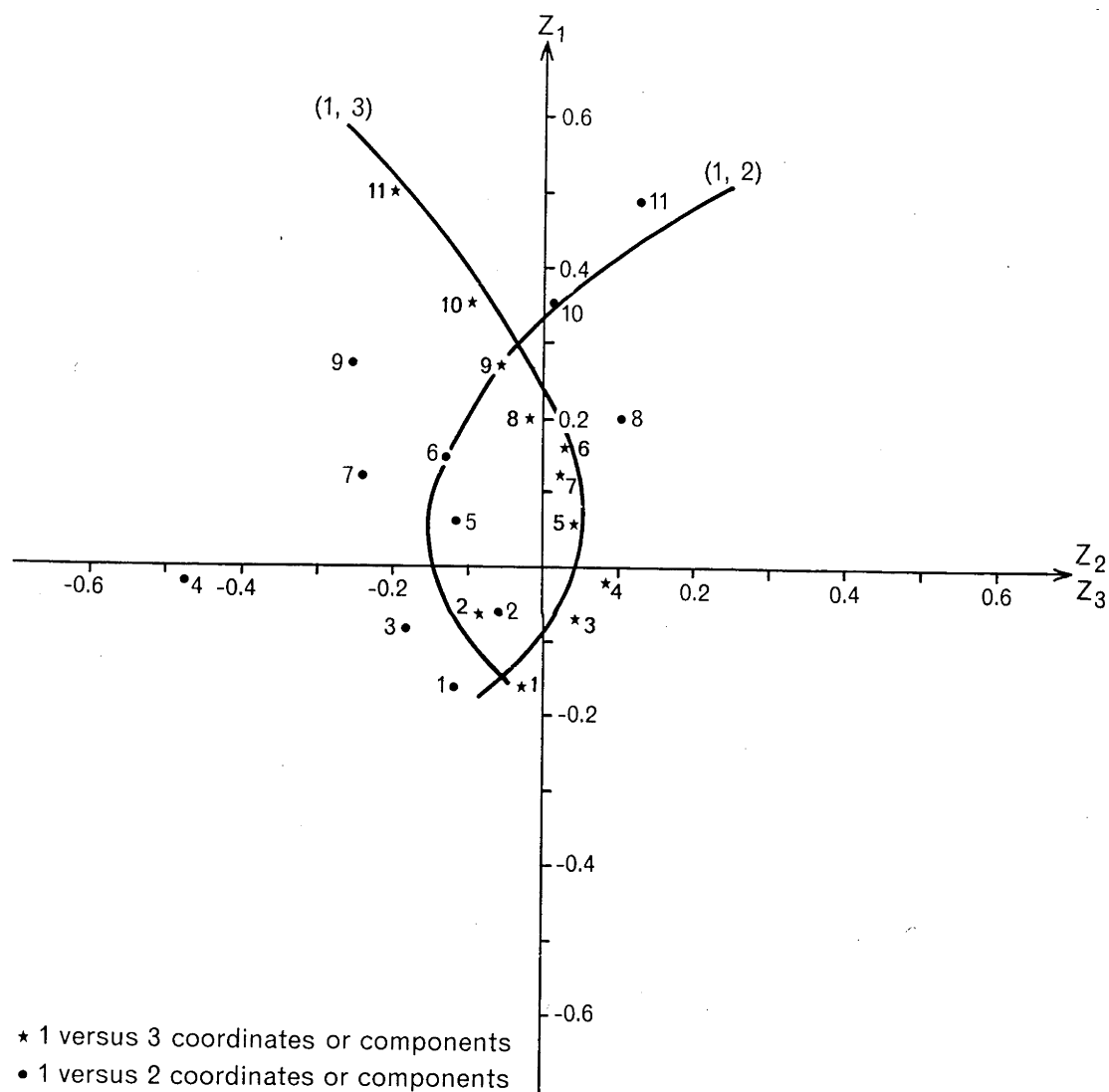


Figure F-2 : Presentation of the 11 locations in the first three principal coordinates or components.



a result, stations with highly different means could be identified as being similar when they are not (Reddy & Virmani, 1982).

### Clustering techniques

Clustering techniques seek to form 'clusters', 'groups' or 'classes' of individuals, such that individuals within a cluster are more similar in some sense than individuals from different clusters. Williams (1971) classifies clustering procedures (Fig. 6-1) into nonexclusive (overlapping) and exclusive (nonoverlapping). The overlapping procedure is of little use in agroclimatic studies. Exclusive classifications are divided into extrinsic and intrinsic. Extrinsic procedures are monothetic divisive strategies used with qualitative data sets. These programs are not well developed (Clifford & Stephenson, 1975). In an intrinsic classification all attributes used are regarded as equivalent. Fager & McGowen (1963) have initiated a non-hierarchical method of species classification where recurrent species groups with defined characteristics have been obtained. Techniques for non-hierarchical types are further divided into serial optimization of group structure, and simultaneously optimization of group structure (relatively undeveloped).

Hierarchical nonoverlapping classification procedures groups whose relationships to one another are readily expressed in two dimensions, generally in the form of a dendrogram. It is difficult to predict how many groups may be required. It seems this can best be decided by a process of trial and error, and reflects personal judgement or bias. Typically it appears best to generate an excess of groups and fuse some of these later. There are two basically different approaches of hierarchical classification procedures, monothetic divisive and polythetic agglomerative. The first involves sub-division of the entities to be classified by one attribute after another considered in sequence (the classic climatic classification procedures). The second, aggregates individuals into groups on the basis of their overall similarity with all attributes considered simultaneously, a preferable approach. There are eight main fusion (classification) strategies that are nonoverlapping, intrinsic, hierarchical, agglomerative-polythetic clustering techniques. FUSE (Turkey, 1954) was designated as a package for the "exploratory analysis of data".

The basic procedures are similar. Beginning with the inter-individual similarity, or distance matrix, the methods fuse individuals or groups of individuals which are closest (or most similar), and proceed from the

initial stage of  $n$  individuals to the final stage in which all individuals are in a single group. Differences between methods arise because of the different ways of defining distance (or similarity) between an individual and a group or between two groups. This suggests that the clustering techniques do not follow the hierarchy as presented above (Williams, 1971) but they all represent different modes of fusion strategies and are based on the attribute state and type of groups required. All follow the same horizontal line rather than vertical lines as depicted in Fig. 6-1.

Using agglomerative-polythetic clustering, eight common strategies are available (Fig. 6-1). They are:

1. NN: nearest neighbour or single linkage;
2. FN: farthest neighbour or complete linkage;
3. UPGMC (centroid): unweighted pair group centroid method;
4. WPGMC (median): weighted pair group centroid method;
5. UPGMA: unweighted pair group method using arithmetic averages;
6. WPGMA: weighted pair group method using arithmetic averages;
7. IS: incremental sum of squares or minimum variance;
8. FB: flexible sorting (for details see Lance & Williams, 1966, 1967b and Burr, 1968, 1970).

Lance & Williams (1966) generalised these procedures under a flexible fusion strategy.

#### Fusion strategies:

The generalised flexible strategy is expressed as :

$$d_{hk} = \alpha_i d_{hi} + \alpha_j d_{hj} + \beta d_{ij} + \gamma |d_{hi} - d_{hj}|$$

where the parameters  $\alpha_i$ ,  $\alpha_j$ ,  $\beta$  and  $\gamma$  determine the nature of the sorting strategy;  $h$ ,  $i$  and  $j$  are three groups containing  $n_h$ ,  $n_i$  and  $n_j$  rows respectively and with intergroup distances  $d_{hi}$ ,  $d_{hj}$  and  $d_{ij}$ . Here,  $d_{ij}$  is considered as the smallest of all distances, so that  $i$  and  $j$  fuse to form a

new group  $k$  with  $n_k = [n_i + n_j]$  elements. Figure F-3 depicts the graphical representation of this equation. In the figure if  $d_{hi} < d_{hj}$  and  $h$  consists of one location ( $n_h = 1$ ),  $i$  consist of three locations ( $n_i = 3$ ) and  $j$  consists of two locations ( $n_j = 2$  &  $n_k = 5$ ). then the new distance  $d_{hk}$  formed after the merger of  $i$  and  $j$ , differ under different fusion strategies (Table F-4), for example:

- NN:  $d_{hk} = d_{hi}$
- NF:  $d_{hk} = d_{hj}$
- WPGMA:  $d_{hk} = 0.5[d_{hi} + d_{hj}]$
- UPGMA:  $d_{hk} = (3/5)d_{hi} + (2/5)d_{hj}$
- WPGMC:  $d_{hk} = 0.5[d_{hi} + d_{hj}] - 0.25d_{ij}$
- UPGMC:  $d_{hk} = (3/5)d_{hi} + (2/5)d_{hj} - (3/5)(2/5)d_{ij}$
- FB:  $d_{hk} = 0.625[d_{hi} + d_{hj}] - 0.25d_{ij}$
- IS:  $d_{hk} = [((3+1)/(5+1))d_{hi} + ((2+1)/(5+1))d_{hj}] - (1/(5+1))d_{ij}$

The above results indicate that NN and FN do not give weight to the entire population of the similarity matrix while computing the new distance matrix after each fusion. In the nearest neighbour strategy, a member enters a cluster at the similarity level equal to the highest similarity between the candidates and any member of the cluster; that is, a single linkage at a given similarity level is sufficient to allow entry to a cluster. The distance between a group and another individual is thus the distance between the individual and the nearest member of the group. The distance between groups is similarly the distance between their nearest member. The farthest neighbour is the exact antithesis of single linkage grouping: fusions are based on the distance between an entirely and the most remote one in a group between the most remote entities in two groups.

In the rest of the fusion strategies, the whole population is taken into account; however, in the case of WPGMC, UPGMC, FB and IS, weight is given to the distance of a group that is currently formed as a separate group while WPGMA and UPGMA considers the population left in the similarity matrix after the formation of the new group. There is no need to consider the distance which has already formed a new group while

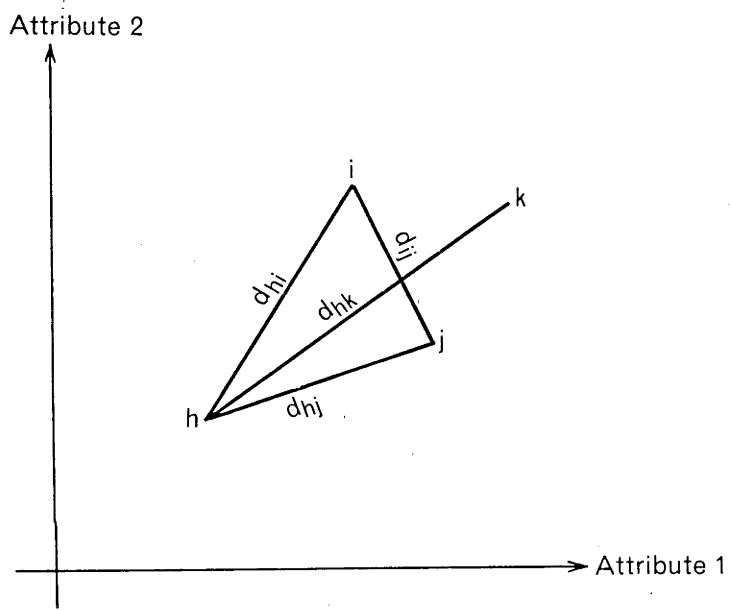


Figure F-3 : Graphical representation of different fusion strategies of clustering.

Table F-4 : Hierarchical agglomerative-polythetic fusion strategies expressed as flexible strategy of Lance & Williams.

Fusion strategy	Flexible strategy parameters <sup>@</sup>				Reference (s)
	$\alpha_i$	$\alpha_j$	$\beta$	$\gamma$	
NN <sup>\$</sup>	0.5	0.5	0.0	-0.5	Sokal & Sneath(1963), Lance & Williams (1967b)
FN <sup>\$</sup>	0.5	0.5	0.0	+0.5	Sorensen(1948), Sokal & Sneath(1963), McQuitty(1964) Lance & Williams (1967b)
UPGMC	$n_i/n_k^*$	$n_j/n_k$	$-n_i n_j/n_k$	0.0	Sokal & Mitchner(1958), Gower(1967), Lance & Williams (1967b)
WPGMC	0.5	0.5	-0.25	0.0	Gower(1966), Lance & Williams (1967b)
UPGMA	$n_i/n_k$	$n_j/n_k$	0.0	0.0	Sokal & Mitchner(1958), McQuitty(1964)
WPGMA	0.5	0.5	0.0	0.0	Lance & Williams(1967b), McQuitty(1966,1967)
FB <sup>\$</sup>	0.625	0.625	-0.25	0.0	Lance & Williams(1967b)
IS <sup>\$</sup>	$\frac{n_h+n_i}{n_h+n_k}$	$\frac{n_h+n_j}{n_h+n_k}$	$\frac{-n_h}{n_h+n_k}$	0.0	Ward(1963), Anderson(1966), Orloci(1967), Burr (1968,1971)

$$^@d_{hk} = \alpha_i d_{hi} + \alpha_j d_{hj} + \beta d_{ij} + \gamma |d_{hi} - d_{hj}|$$

<sup>\$</sup>NN = Nearest neighbour; FN = Farthest neighbour; FB = Flexible;  
 $\beta = -.25$  ;IS = Incremental sums of squares.

$$^*n_k = n_i + n_j$$

computing the new distance, as for example  $d_{ij}$  which relates to  $i$  and  $j$  is already taken into account in the formation of group  $ij$ .

With UPGMA, a candidate for entry to a cluster is admitted at a similarity level equal to the average similarity between the candidate and the existing measure of the cluster. As the similarity levels are lowered, remaining entities join one or another of the clusters. These procedures give an equal influence throughout the process to each individual. In the case of UPGMC, fusion of an entity into a group, or fusion of pairs of groups depends on the coordinates of the centroid. Groups are fused on minimal distance between centroids. Gower's (1967) centroid method is perhaps the most attractive fusion strategy from a geometric point of view, taking into account the position of all members of each group in determining fusion. However, its exact geometric representation is still not entirely satisfactory (Webster, 1979). In centroid sorting, if a small group fuses with a large one, it loses its identity and the new centroid may come to lie entirely within the confines of the larger group. To indicate the individuality of the small group, it is desirable that the group obtained after fusion should be intermediate in position. This is effected in WPGMC (or FB) sorting by regarding the groups as being of unit size and obtaining a weighted median position after fusion (Clifford & Stephenson, 1975). This strategy was apparently first suggested by Gower (1966) with a view to preventing large groups from dominating classifications to the exclusion of smaller groups. In WPGMA, like WPGMC equal weights are given to both groups irrespective of the number of entities in the individual groups.

IS has been proposed by several workers: Ward (1963) who described it as an "error sum of squares" strategy, Anderson (1966) proposed it under the name of "minimum variance clustering" and Orloci (1967) also developed the strategy under the "sum of squares method" and finally Burr (1968, 1970) coined the term "incremental sums of squares". Squares of Euclidean distance is used as a distance measure and after uniting the pair of elements whose squared distance is minimum, subsequent entities are fused such that the sum of squared distances within a cluster increases by a minimum. Because the total sum of squares is constant, if the sum of squared distances within a cluster increases minimally, then it follows that the squared distance between clusters is increased maximally.

Ward (1963) and Burr (1970) point out clustering could be based on the minimum sum of squares within clusters resulting from each fusion rather than on minimal increase of this value. Such a procedure frequently leads to absurd results and is not recommended (Clifford & Stephenson, 1975). This clustering method may also be applied with dissimilarity measures. A method of clustering allied to that just described is one in which there is a minimal increase in the variance (Wishart, 1969; Anderson, 1971) rather than the sum of squares within a cluster at each step in the fusion cycle. Its formulation is given by Burr (1970), however, its properties are not well known.

#### **Comparative analysis:**

Clusters were determined using the eight fusion strategies for the data matrix presented in Table F-1 with three similarity measures obtained from (i) GM- Gower metric with 11-attribute data matrix, (ii) SEM- standardized Euclidean metric with 11-attribute data matrix and (iii) EM- Euclidean metric with 7-attribute data matrix representing 7 principal coordinates from Gower's principal coordinate analysis. The results are presented in Fig. F-4.

Using NN strategy the grouping under EM is poor. This is not improved much with the other two measures but the clarity is slightly better with GM. Using FN, groups formed under GM & SEM are similar to those under NN. Groups formed under EM appear to be more reasonable. Groups formed under FB are anomalous while the groups formed under UPGMA appear to be acceptable. Groups formed under WPGMA with GM are similar to UPGMA, but the groups formed under other two measures show mis-classifications. Groups formed under UPGMC & WPGMC show some mis-classifications. Groups formed under IS with SEM & EM are similar and good. The groups formed under GM show poor clusters.

The above results suggest that the clusters formed under no two similarity measures are similar, even under similar fusion strategies. The clusters formed under no two fusion strategies are similar. It generally appears that the first order metric (Gower metric) with first order fusion strategy (UPGMA & WPGMA) is the best while second order metric (Euclidean metric) with second order fusion strategy (IS) is the second best.

#### **Tests of significance of results:**

Belbin (1982) suggested a simple test to determine distortional

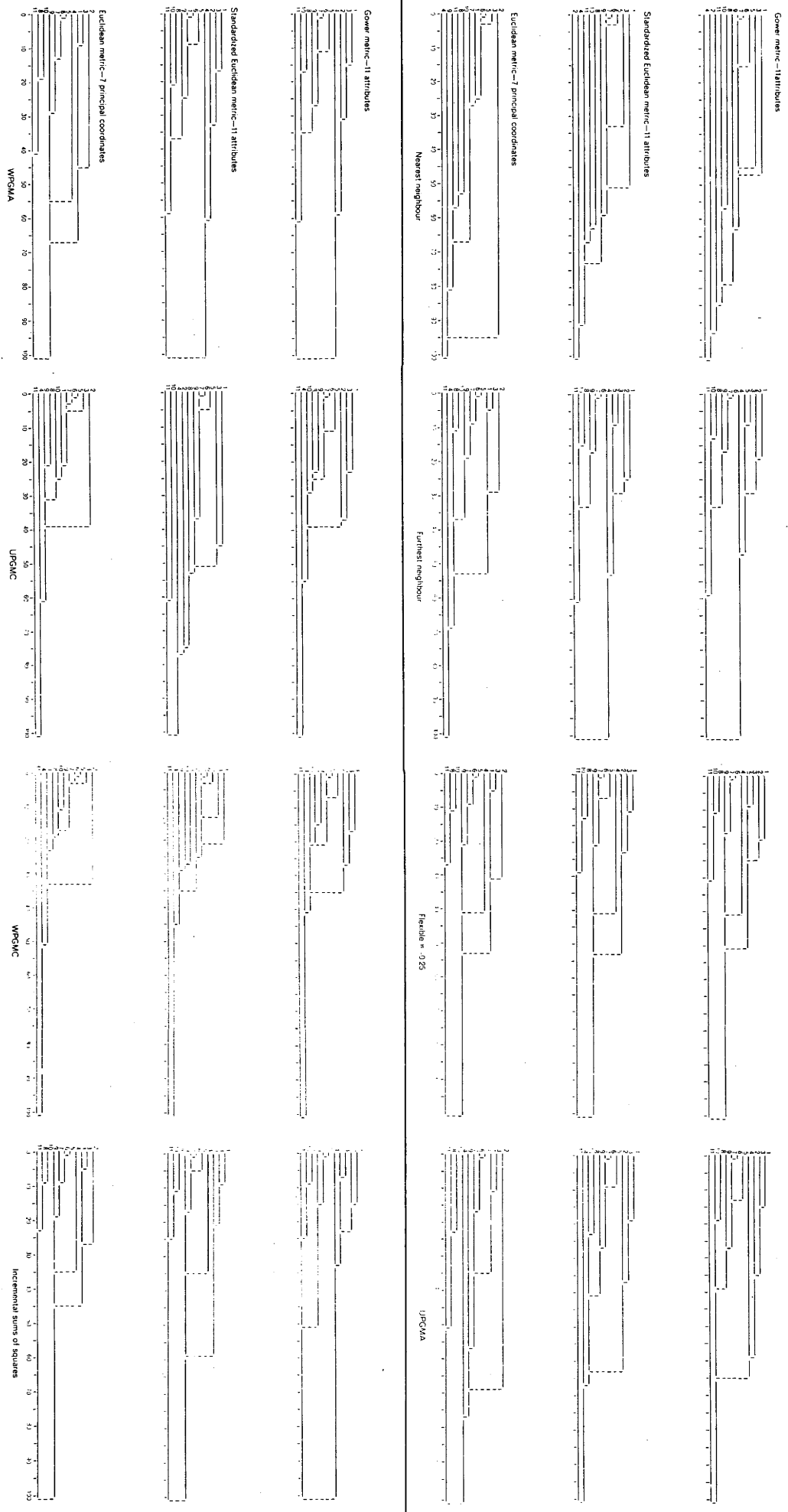


Figure F-4 : Dendrogram of different fusion strategies with different similarity metric and data matrices.



effects (Lance & Williams, 1967a & b; Williams et al., 1970) called the space distortion coefficient (SDC) defined as the ratio of level of last fusion (the maximum dissimilarity as suggested by dendrogram-  $D_1$ ) to large dissimilarity in the association matrix- $D_m$ . i.e.,  $D_1/D_m$ . Values around 0.6 indicate space-conservation; while values less than 0.4 suggest strong-contraction and values greater than 0.9 indicate space-dilation. For the example presented in Fig. F-4 these estimates are presented in Table F-5. This table suggests that NN and UPGMC are space-contracting; UPGMA, WPGMA & WPGMC are space-conserving and FN, FB and IS come under space-dilating strategies. However, according to Belbin (1982) UPGMC & WPGMC are space-dilating strategies and Williams (1967a) and Sneath & Sokal (1973) observed UPGMC as space-conserving strategy. A reasonable rule with regard to choice of strategy is to utilize only space-conserving strategy unless data suggests specific effects may assist interpretation of structure (Belbin, 1982). Therefore, in terms of space-conservation UPGMA, WPGMA & WPGMC are the more reasonable fusion strategies. This criterion however, does not specify the significance of clusters or mis-classifications.

It must be admitted that one of the biggest deficiencies of cluster analysis is the lack of rigorous tests for the presence of clusters, and the lack of tests for the significance of clusters that are found (Lenington & Flake, 1974; Ling, 1971; Sneath & Sokal, 1973). Although some criteria have been proposed (Goodall, 1966a,b), the main deficiencies are the specification of suitable null hypotheses, the determination of the sampling distribution of the distance (or similarity) between data points and the development of flexible test procedure.

Rohlf (1974) summarizes a number of different measures for comparing two dissimilarity matrices, however most are either difficult to interpret or rarely used or both (Belbin, 1982). One such measure listed by Rohlf that is in common usage and simple to interpret is the Cophenic correlation coefficient (Sokal & Rohlf, 1962). This measure compares the dissimilarities implied between all individuals from the fusion table or dendrogram with those of the original measures of association. This is the Pearson's Product Moment correlation coefficient for observed (original) and expected (dendrogram) dissimilarities. As might be expected, the space-conserving strategies would, on average, produce the best correlation coefficient, because the correlation utilizes only half its range

Table F-5 : Coefficients of comparison between different fusion strategies using different similarity measures with different types of attributes.

Simil- arity metric	Coeff- icient	Fusion strategies <sup>@</sup>							
		NN	FN	FB	UPGMA	WPGMA	UPGMC	WPGMC	IS
GM	C	.426	.540	.512	.744	.606	.672	.671	.508
	B	.336	.244	.272	.110	.150	.246	.199	.357
	S	.302	1.000	1.070	.676	.728	.497	.658	1.320
SEM	C	.407	.521	.567	.731	.592	.596	.635	.566
	B	.269	.222	.262	.102	.140	.259	.186	.340
	S	.356	1.000	1.122	.703	.760	.375	.646	1.318
EM	C	.218	.498	.455	.504	.463	.529	.513	.452
	B	.216	.158	.231	.116	.136	.175	.156	.285
	S	.363	1.00	1.039	.576	.810	.491	.685	1.246

\* GM = Gower metric; SEM = Standardized (with S.D.) Euclidean metric;  
 EM = Euclidean metric (In the case of GM & SEM, the similarity matrices are computed from the data matrix in Table F-1; while in the case of EM this is obtained from the 7 principal coordinate data matrix);  
<sup>\$</sup>C = Cophenetic correlation coefficient; B = Bray & Curtis coefficient;  
<sup>S</sup> = Space distortion coefficient;  
<sup>@</sup>NN= Nearest neighbour; FN = Farthest neighbour; FB = Flexible  $\beta=-0.25$ ; IS = Incremental sums of squares.

(inverse relationships should be non-existent). According to Belbin (1982) an alternative and simpler approach to this problem is to use the Bray & Curtis (1957) measure, expressed as:

$$\text{Fidelity} = \frac{\sum_{k=1}^n [d_{ik} - d_{jk}]}{\sum_{k=1}^n [d_{ik} + d_{jk}]}$$

Fidelity = 0 for perfect match and 1 for complete mismatch.  $d_{ik}$  = value of  $k^{\text{th}}$  comparison of original dissimilarity and  $d_{jk}$  = value of  $k^{\text{th}}$  comparison of dendrogram. a disadvantage of this type of measure is that it fails to detect the differences between different structures; markedly different dendrograms may produce the same fidelity value.

Table F-5 presents the above-mentioned two coefficients for all the cases presented in Fig. F-4. From this table it is seen that in terms of the Bray & Curtis value, UPGMA is the best fusion strategy with all the three similarity measures and for the Cophenetic correlation coefficient, it is the best out of three for two similarity measures using the 11 attributes and the second best using a 7-attribute matrix. In terms of the Bray & Curtis value, the second best method is WPGMA with all the three similarity measures, however, in terms of the Cophenetic correlation coefficient, UPGMC & WPGMC appear preferable to WPGMA. Even in the case of WPGMA, it is relatively high. The Bray & Curtis value in WPGMC appear to be superior to UPGMC, and also suggests that IS is the poorest strategy. Cophenetic correlation coefficient suggests that NN is the poorest strategy. Even though FB and WPGMC are quite similar functionally, they differ substantially. These results suggest, therefore, first preference should be given to UPGMA followed, in order, by WPGMA, WPGMC, UPGMC, FN, FB, NN and finally IS.

Harbough & Merriam (1968) did not find any difference between the results obtained from standardized correlation coefficient or Euclidean distance using either UPGMA or NN in terms of structure in geological studies. However, they found a slight difference in levels at which the groups are observed. Boyce (1969) states that the overall patterns of relationship produced by the UPGMA, WPGMA, WPGMC with measures of correlation are very similar and there are no topological differences between the dendrograms based on averages although the levels at which corresponding stems join do differ. In agroclimatic classification studies, however, the level at which the groups are found are very important.

Russell (1978) used the Canberra metric with FB fusion strategy to classify global climates. He used 16 monthly measured and derived attributes. The classification, however, does not distinguish location with very different climatic regions. For example, Bellary, a very dry location, is grouped with Hyderabad, Sholapur, and Vishakhapatnam wetter locations. Similarly Poona with Jabalpur & Raipur; Bikaner & Jodhpur with Allahabad; Dwaraka with Bombay. These results may reflect inappropriate attribute data as much as they do the classificatory method.

### **Minimum spanning tree**

The minimum spanning tree (MST) of the set of points is the network of minimum total length such that every point is joined by some path to every other point, and no closed loops occur. Because of this characteristic MST was treated as a separate classificatory procedure. Eventually  $n-1$  links are required to connect  $n$  points. Several methods of computing the MST are known, of which the algorithm of Prim (1957) is the most efficient (Rose, 1969). Wroclaw Taxonomy (Florek et al., 1951) also uses the MST. The MST uses the similarity matrix, and from it the single linkage cluster analysis (NN) of Sneath can be computed directly (Gower & Ross, 1969).

MST can be derived more efficiently than the corresponding dendrogram, and MST reveals not only which pair or pairs of individuals are most alike, but also which pairs of individuals in different branches of the tree are most similar (Webster, 1979). MST is thus a useful way of exploring the distribution of individuals in character space and complements ordination analysis. The disadvantage of the MST is that it provides no information about how the various branches of the tree should lie relative to each other. This can be overcome for small trees by drawing the tree on the vector diagram provided by ordination results. Groups so defined are not clusters in any taxonomic sense but are purely a device to lessen computation. MST will be unique if the input data does not contain any identical similarities. MST may also be used to check the groups produced by an intensely clustering strategy for misclassifications.

### **DISCUSSION**

The most efficient way of grouping is obviously cluster analysis with the results normally presented in the form of a dendrogram (Mayer et al., 1953 introduced this term). Sneath & Sokal (1973) state that "there are as yet no satisfactory methods for testing from the similarity matrix itself

whether clustering or ordination is most appropriate, although a high Cophenetic correlation may suggest that a dendrogram is a reasonable representation of a well clustered distribution". It is sometimes possible to discard a method completely because the results appear nonsensical, but in others the choice of which is the best can not readily be made. In taxonomy, an experienced worker can generally detect an entity which appears to have been misclassified. He or she can also judge good and bad classifications. **they make these judgements on the basis of experience and intuition which may not be easy to quantify or even describe.** In the clustering technique, angles between branches are of no importance, but points of origin of branches are very important. Williams & Lance (1969) believe that inadvertent chopping of continuous variation into somewhat arbitrary clusters does not usually damage the analysis irretrievably, because the continuity is generally fairly evident. Clifford & Stephenson (1975) state that it is not always desirable to truncate each branch of a dendrogram at the same level. Though differential truncation involves subjective decisions, it can be argued that objectivity is maintained if the cut-off values are explicitly stated. In contrast, ordination may not describe sharp discontinuities if they are not displayed in the first few dimensions. The major disadvantage with the ordination technique is the difficulty in interpretation: the components or coordinates do not contain the physical meaning even though each component indicates the attributes that contributed significantly. MST provides no information about how the various branches of the tree should lie relative to each other, therefore no clusters are defined in any taxonomic sense.



